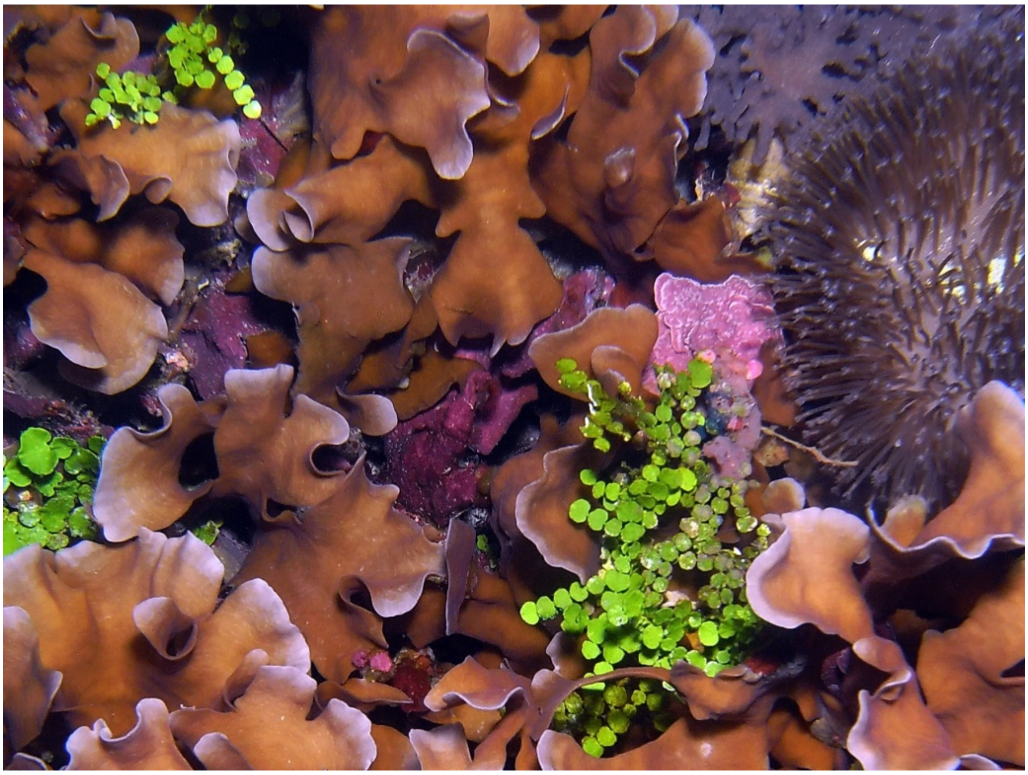
Monitoring Study S5

Montara: 2011 Offshore Banks Assessment Survey



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Executive Summary

On Friday, 21st August 2009, accidental loss of control from the Montara H1 well resulted in the release of hydrocarbons in the form of gas, condensate and crude oil into the Timor Sea. The release ceased 75 days later on 3 November. On 9th October 2009, PTTEP Australasia (Ashmore Cartier) Pty. Ltd (PTTEPAA) and the Department of the Environment, Water, Heritage and the Arts released a *Monitoring Plan for the Montara Well Release Timor Sea* that included a subcomponent (S5) to investigate the effects of the uncontrolled release on the submerged banks and shoals of the Timor Sea. This sub-component was formally triggered in November 2010. In January 2011, The Australian Institute of Marine Science (AIMS) was commissioned by PTTEPAA to conduct the S5 study. The results of the survey work, completed in March and April 2011, approximately 16 months after the uncontrolled release, are reported here.

The objectives of the S5 study, as outlined in the Monitoring Plan, were to identify and quantify physical character of the shoals (depth, substrate), identify the biota and community structure, estimate the potential exposure to surface oil and dispersed oil, and identify any obvious damage to the associated communities. In the absence of any pre-spill baseline data, the objectives were addressed by examining the attributes of nine banks and shoals ranging from <3 to ~150 km away from the HI Well Head Platform (WHP), and selected to represent a gradient of high, medium and low exposure to the hydrocarbons released from the WHP. Surveys were undertaken of (a) sediment hydrocarbon levels, (b) shoal bathymetry using multi-beam swath mapping, and (c) benthic habitat and fish community composition (to a depth of approximately 60 m) using various remote imaging techniques. Since the shoals in the Timor Sea, have never been subject to such a detailed scientific analysis, the study had a high discovery component.

Sediment Hydrocarbons

A number of different sampling strategies were used to examine the pattern of sediment hydrocarbon contamination associated with the uncontrolled release. This included sampling predominantly sandy sediments around the base of the shoals and, where possible, sandy sediments of the plateau areas of a number of shoals. For comparative purposes, samples were also collected around the Montara WHP, along a transect line extending ~35 km from the platform towards Vulcan and Goeree shoals, and around the natural hydrocarbon seeps at the Cornea oil and gas field.

These surveys indicated a widespread, low-level presence of degraded oil and the presence of concentrations at some sites (for example around Eugene McDermott shoal and the Montara WHP) that were nearly double levels measured before the uncontrolled release, including sediment collected from the Cornea seep area. Where detected, oil residues were found to be severely degraded having lost more of the low molecular weight PAHs, and with gas chromatography-mass spectrometry profiles typical of degraded oil. Many of the extracts contained a full suite of PAHs, sterane and triterpane biomarkers, which would be expected for a degraded crude oil.

The spatial patterns of hydrocarbons in relation to the distance from the Montara well head platform were consistent with hydrocarbons originating from the Montara reservoir. However, source matching could not be achieved because of the extensive weathering of the oil. Previous studies in the area have shown there is a background presence of petroleum hydrocarbons that could originate from the oil industry, passing ships, discharge from fishing boats and natural oil seeps. Since source matching was not possible, the origin of the oil in the sediment remains equivocal. Irrespective of the source, the levels of hydrocarbon in the sediment at the time of survey were very low, and several orders of magnitude lower than levels at which biological effects become possible.

Given the degradation of the oil, and considerable time that had passed before the commission of the study, the true spatial extent of the contamination will never be fully known. In addition to establishing routine regional hydrocarbon measurement as part of baseline monitoring, it is recommended that in the event of future uncontrolled releases of this type and magnitude, sampling of hydrocarbons in sediments is initiated immediately after a well is under control.

Biodiversity

The seabed on the flat, plateau-like areas of the shoal tops were found to be dominated by benthic primary producers, including varying amounts of algae and hard corals, interspersed with sand and rubble patches. Both benthic communities and fish faunas of the shoals were diverse and varied within and between shoals. The biota on these shoals were typical of shallow tropical reef systems studied elsewhere. The attached seabed (benthic) biota included many coral and algal species and are likely to mirror regional coral reef diversity. A multivariate analysis of the community structure recognised six assemblages of fishes among the shoals, principally determined by depth, the amount of reefal substrata and the size (area) of the shoal plateau. Species level identifications found the fish fauna to be more diverse than seen on the Great Barrier Reef on equivalent seabed features.

The submerged shoals were found to support many of the same species in common with the emergent coral reefs of the region (such as Ashmore and Cartier Reefs and the Scott Reef complex). They may, therefore, act as stepping stones for enhanced biological connectivity among the reef systems of Australia's northwest. The shoal habitats also provide an additional regional reservoir of megafauna species, such as sharks and seasnakes, hitherto typically associated with the emergent reefs.

There were no obvious signs of a recent major disturbance to the benthic biota on the shoals, with one exception. At Vulcan Shoal, located closest to the Montara well head platform, a very significant loss of seagrass was apparent in 2011 when compared with data from surveys conducted by AIMS in 2010, six months after the uncontrolled release. The causes of this loss, which occurred in the interim period between the two field surveys 6-16 months after the release ceased, cannot be reliably determined. Sediment samples confirm that Vulcan Shoal, which lies 33 km from the Montara well head platform, had hydrocarbons from some source present and that this exposure, while low, was higher than other shoals in this study. Sensitivity of some seagrass species to hydrocarbons, more so in the presence of dispersants, has been reported in the general literature. However, as the 2010 survey, six months after the uncontrolled release, found the seagrass in excellent apparent health, a highly delayed effect from the uncontrolled release resulting in a change sometime between 6-16 months afterward seems unlikely. Only extensive remnant rhizomes remained in 2011, although there was evidence of a few new leaf shoots developing from the remnant rhizomes. In contrast the hard corals on Vulcan Shoal were normal in appearance and had not decreased in abundance during the same period, suggesting that the cause of the seagrass loss was either selective to seagrass or perhaps physical in nature and mostly affecting loosely attached biota. A storm or other source of strong seabed shear forces, scouring the seagrass and other loosely attached organism present on rubble and gravel substrate, may have been responsible. An analysis of images from the same locations between the two years tends to support the hypothesis of a physical scouring event, as not just seagrass cover but the abundance of *Halimeda* algae and didemnid ascidians in the same mixed rubble and coarse sand areas, were also markedly reduced. Nonetheless, based on available track data, there was no evidence of a cyclone directly disturbing Vulcan Shoal during the period in question. A variety of other agents of rapid change in the seagrass community were considered, including possible predation by an out-breaking population of urchins or thermal stress due to abnormal sea water temperature events. Analysis of 2010 and 2011 images for urchins found no evidence for large populations on Vulcan Shoal, bearing in mind images were mostly collected during daylight. A potential role of seawater temperature cannot be excluded. Analysis of blended satellite sea surface temperature data does reveal a rapid change from unusually warm conditions in 2010 to unusually cool conditions in 2011. The cause of the seagrass loss at Vulcan Shoal

cannot be determined, however, there would be merit in conducting another survey to confirm whether this area has recovered within one - two years.

There were three indices of potential exposure to hydrocarbons used in our spatial analysis of fish communities on the shoals. These metrics included distance from the Montara well head platform and hours of exposure to the modelled Montara plume, while the third, adjusted hydrocarbon concentrations in sediments, was also used because there was demonstrated spatial variation between shoal locations even though this variable could not be directly linked to the uncontrolled release. Data were explored using two statistical approaches. The first technique considered all environmental and exposure variables simultaneously and found that depth and aspect were the main predictors of the observed patterns in fish and benthic data, rather than exposure to hydrocarbons from the Montara well head.

The second approach established relationships between fish assemblages and habitat and then considered whether hydrocarbon exposure explained additional variation in the fish assemblages. These analyses found suggestions of a decrease in diversity (5-10%), total abundance (5-30%) and increases in mean size (2-10%) of fishes at those shoals closest (within 50 kms), to the Montara well head platform.

While these results do not exclude a potential effect of exposure to hydrocarbons and dispersants on the fish communities, the observed variations between shoals appear to be dominated by natural processes. The spatial patterns correlated with metrics of uncontrolled release influence detected in some components of the fish communities leave open a possible influence from the uncontrolled release. Our results underline the critical importance of appropriate baseline data obtained prior to an uncontrolled release, for use in the definitive identification or exclusion of impacts.

Suggested additional surveys and analysis

The causes of changes in seagrass cover at Vulcan Shoal and variations in the patterns of fish diversity, abundance and size among shoals cannot be determined with certainty using existing data. Additional temporal and spatial data may provide further insights into possible causes and help to determine if these patterns are persistent or transient. A broader survey would also reveal if the observed spatial patterns are fully centered on the Montara well head platform. We suggest the following actions:

1. A detailed investigation of regional disturbance histories using metocean data that may explain the loss of seagrass at Vulcan Shoal.

2. Monitoring of the benthic communities at Vulcan Shoal to document any further changes or recovery of seagrass beds. Resurveying of the other shoals is also recommended in order to determine if seagrass meadows and other benthos tend to change significantly over time under normal conditions.

3. The inclusion of more distant sites into any further monitoring study sites, in order to determine if the observed patterns remain consistent with a possible influence from the Montara uncontrolled release. Such targeted monitoring would need to determine the extent of cross-shelf and latitudinal patterns in species richness, total abundance and size of fishes.

1. Introduction

1.1 Regulatory Response leading to the Banks and Shoals study

On 21st August 2009, loss of control from the Montara H1 well resulted in the release of gas, condensate and crude oil from the Montara reservoir through Montara Well head platform (WHP) into the Timor Sea. On 9th October 2009, PTTEP Australasia (Ashmore Cartier) Pty. Ltd (hereafter PTTEPAA) and the Department of the Environment, Water, Heritage and the Arts (DEWHA, now the Department of Sustainability, Environment, Water, Population and Communities, DSEWPaC) released a Monitoring Plan for the Montara Well Release Timor Sea (hereafter the Monitoring Plan)(PTTEPAA 2009).

The Monitoring Plan contained both operational (designated with an O prefix)and scientific (designated with an S prefix) monitoring components in accordance with Australia's National Plan to Combat Pollution of the Sea by Oil and Other Noxious and Hazardous Substances (the National Plan). Operational monitoring is monitoring undertaken during a response, focussed on providing information of use in planning or executing the response, and scientific monitoring is focused on non-response objectives such as estimating environmental damage and post response recovery. Also incorporated within the Monitoring Plan were a number of 'triggers' which if initiated, would prompt the various sub-components of scientific monitoring to be undertaken.

One of the studies of the Monitoring Plan was scientific monitoring of the banks and shoals (referred to as Study S5). These submerged biological/geological features were identified in the monitoring plan as key habitat and community types in this region. The triggers to initiate Study S5 were:

- Oil slick passing over the banks and detection of oil at depths of >5 m (data from Study O2) including under dispersant treated oil;
- Oil spill trajectory modelling predictions (Study O1) indicating the above.

As noted above, detection of oil at depths of >5 m was to be obtained from operational monitoring Study O2 (Monitoring of Oil Character Fate and Effect) of the Monitoring Plan, however, the O2 study failed to find a direct correlation between fluorescence measurements and hydrocarbons in the water (see AMSA 2009) and it was, therefore, recommended that '..for environmental effects assessment purposes, the distribution and concentration of dispersed oil should be modelled using available 3D models..'. That study was conducted by Asia-Pacific ASA under Scientific Monitoring program S7.2 of the Monitoring Plan for the Montara Well Release Timor Sea (APASA 2010b) , and a final report released on 4th October 2010. The report was released publically on 19th November 2010.

In the S7.2 report, 11 dispersant events were simulated using three dimensional (3D) modelling, and three of these indicated the potential for hydrocarbons to reach some of the banks and shoals, creating concentrations (at the depth of the shoal) of '..< 0.010 ppm or < 10 ppb) and for durations of less than 18 hours..' (APASA 2010b). Thus, the Study 02 (operational monitoring) effectively triggered Scientific Study S7.2 and the results of study S7.2 formally triggered the Study S5 (scientific monitoring program) '..Offshore Banks Assessment survey..' of the Monitoring Plan for the Montara Well Release Timor Sea (PTTEPAA 2009).

On 11th November 2010, the Australian Institute of Marine Science (AIMS) was contacted by PTTEPAA with a view to formerly submitting a proposal for Offshore Banks Assessment survey (S5). The study was conducted in March and April 2011 and the results are presented here.

1.2 Bioregional context and existing information on shoals

The Montara Well Head Platform (MWHP) uncontrolled release (21 August – 3 November 2009) occurred within the North West Shelf marine biogeographic province defined within the 'Integrated Marine and Coastal Regionalization of Australia (IMCRA): ecosystem-based classification scheme for marine and coastal environments' (IMCRA 2006). Within the province there are both submerged and emergent reefs and cays along the outer edge of the continental shelf extending from the Lydoch and Troubadour Shoals in the Arafura Sea (north of Darwin) to the Rowley Shoals north-west of Broome. This 246,404 km^2 area is also referred to as the Oceanic Shoals (OSS) meso-scale region within the IMCRA classification (IMCRA 2006). The limits of this region are nominated as lying between 18° south and 119° east, and 10° 30' south and 131° east.

A collation of industry survey data from shoals in the central part of this bioregion in the mid-1990s (Heyward et al. 1997) noted the abrupt bathymetry of the shoals and found that high diversity ecosystems could be found there. A number of shared biological features and habitat types were reported, but also marked differences between individual shoals were found. The offshore waters in this region tend to be clear, enabling some phototrophic species, such as algae and corals, to thrive even at depths of 50 m or more in places. As many submerged shoals may rise to within 15-50 m of the sea surface, shallower habitats exposed to adequate sunlight have at least the potential to support a diverse floral and faunal composition similar to the emergent oceanic reef systems. Due to the remoteness of the region, however, most of the banks and shoals are either unstudied or poorly characterized. In 2010, the lease operator, PTTEPAA, requested a preliminary assessment of benthos on the tops of Barracouta and Vulcan Shoals, two submerged shoals located 55 km and 27 km west and south-west respectively of the MWHP (see Figure 1.1), that were likely to lie under the area covered by some components of the Montara uncontrolled release. That survey was effectively a pilot study, providing preliminary data to aid in planning a broader assessment of the numerous shoals in the region.

The objective of that preliminary work, in addition to providing a first look at contemporary shoal habitats closer to the uncontrolled release source, was to assist the company and the Commonwealth Government (through the responsible agency, the Department for Sustainability, Environment, Water, Population and Communities –DSEWPaC) in understanding some of the habitat types that might be encountered and gain insight into the issues of spatial variability within and between shoals. This information would then assist in the design of a more detailed and spatially comprehensive study to detect possible impacts in the event that the Banks and Shoals component (S5) of the Montara Monitoring Plan developed by the company and DSEWPaC was formally triggered.

Extensive survey sampling across the plateau areas of Barracouta and Vulcan shoals in April 2010 - conducted six months after uncontrolled flow from the Montara H1 well had been stopped, revealed that: (a) both contained diverse biological communities (b) there were pronounced differences within and especially between the two shoals in the relative abundance of dominant groups and (c) there were no obvious signs of a major, recent disturbance. This study, however, was not designed to detect any smaller or more localized impacts, nor could it determine if any other shoals in the region had been affected by the uncontrolled release at the MWHP.

The 2010 surveys confirmed observations on shoals elsewhere in the bioregion (Heyward et al. 1997) that on the shoal plateaus there is adequate light to support many photosynthetic organisms

on the seabed. Consequently, the shoals have the potential to support both planktonic primary production and benthic primary producer habitat (BPPH). Extensive sampling across the general plateau areas, in depths of 15-50 m, found this to be the case for Barracouta and Vulcan Shoals, with varying amounts of photosynthetic organisms, typically algae, hard coral or seagrass recorded. Based on those results, a number of additional potential shoal-type habitats were identified, solely on available bathymetry, within 100 km of the MWHP site (Figure 1.2).

The results of the initial survey support the idea that the submerged shoals in the Timor Sea can support diverse tropical ecosystems and in many cases, particularly where the depths are shallow enough to support phototrophic organisms, may support a typical array of coral reef primary producers and associated biodiversity. Based on general observations in this region, benthic primary producers such as algae and reef building corals can be dominant to depths of 50-60 m at least. On this basis, the preliminary analysis of the bathymetry around the Montara Well Head platform identified more than 20 possible shoal features within 100 km distance and >100 similar bathymetric features within 200 km (Figure 1.2). Given the biological differences observed between Vulcan and Barracouta shoals in 2010, only the most general predictions could be made regarding the nature of marine life on any of these other unsurveyed shoals around the well head. It was not clear if unsurveyed shoals under the uncontrolled release supported unusual or more complex biological communities with differing sensitivities to those surveyed in 2010. Similarly, the pathways for any interaction or potential exposure that may have occurred between the Montara uncontrolled release and the benthic communities of Barracouta and Vulcan Shoals may not be the same for other shoals that lie under the uncontrolled release area.

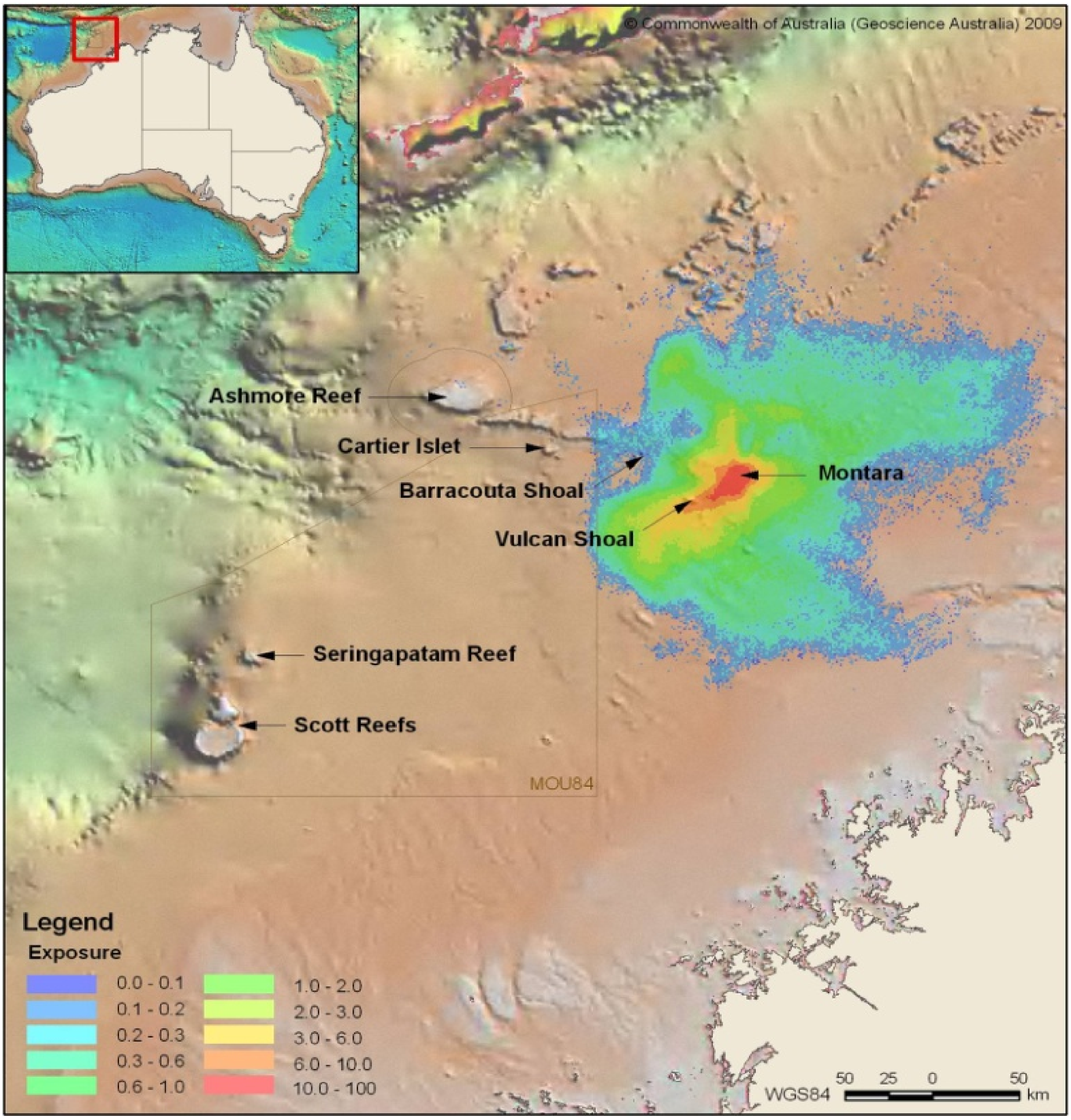

Figure 1.1. Location of Vulcan and Barracouta Shoal study sites surveyed in 2010 in relation to modelled relative exposure map of the oil spill. Image of the spill developed by Asia-Pacific ASA in another of the independent studies triggered under the monitoring plan developed by the company and DSEWPaC and released by the agency. This is a relative exposure map representing up to 99.9% of occurrences of visible surface oil associated with the Montara incident. It is important to note that the area shown does not represent the extent of any oil slick observed at any time during the uncontrolled release incident. It is a summation of the area within which isolated patches of oil and wax were observed by aerial or satellite observations and oil spill trajectory modelling.

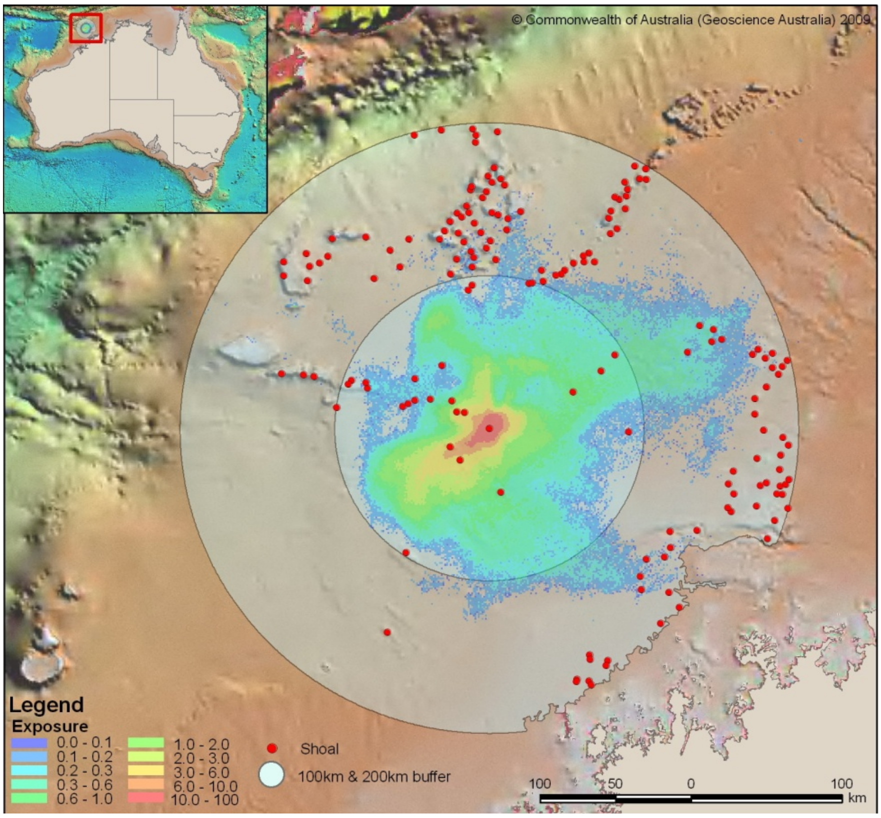

Figure 1.2. Desktop identification by Heyward et al (2010) of potential shoal-type habitat locations in the general vicinity of the modelled Montara uncontrolled release exposure. Shoals type features, indicated by red dots, were identified from the Australian hydro-geographic charts A00314, A00319 and A00320 and defined as abrupt submerged features rising from deeps > 50 m. Depths of < 50 m along the coast of Australia have been excluded from the analysis. Due to much of the region being inadequately surveyed this analysis provided only an initial guide to potential 2011 survey locations. The exact location and spatial extent of some features remains uncertain.

The lack of pre-existing baseline data for biodiversity on shoals near the MWHP constrained the types of analysis that could be undertaken to test for any effect of the uncontrolled release. As a before-and-after comparison was not possible, it was decided to select a series of the larger known shoal locations that represented a gradient of potential exposure, from high to low, at increasing distance from the uncontrolled release source. It was envisaged that sampling this set of shoals along such a potential exposure gradient would allow an analysis of spatial patterns in the benthic and fish communities, with the ability to test if distance from the hydrocarbon source influenced these patterns.

The pilot survey (Heyward et al. 2010) provided some guidance for sampling methods and level of effort required to characterise the major benthic habitats on the shoal plateaus. It was also clear from that study that high resolution bathymetry would be desirable in future work to facilitate modelling and implement efficient sample strategies for benthic biodiversity.

As a result of a formal triggering of component S5 of the Montara Monitoring Plan, (PTTEPAA 2009), a more comprehensive assessment of submerged shoals was undertaken, at the request of PTTEPAA in April 2011. The study was a larger and more sophisticated assessment than the 2010 pilot, designed to include many more shoals, comprehensive multibeam swath mapping and measures of fish diversity, in addition to gathering data on the benthic habitats and sediment hydrocarbons. This document reports on the findings of those surveys.

1.3 2011 Shoal Selection and Trip Planning

The two shoals, Vulcan and Barracouta, surveyed in 2010 as a preliminary Montara investigation (Heyward et al. 2010) were included for repeat surveying in 2011. Additional potential shoal-type habitats were identified from available bathymetry and Australian navigational charts (Aus314, Aus319, Aus320) that lie within 200 km of the Montara WHP and were shoals rising from deeper than 50 m. The modelled relative surface oil exposure map (Asia-Pacific ASA 2010) of the uncontrolled release was loaded into a Geographical Information System (GIS) and all potential shoals were allocated a rating (high, medium, low, none) based on exposure. All shoals with high or medium exposure were automatically included for environmental assessment. Shoals outside of Australian Commonwealth waters were excluded and representative shoals with low or none exposures were selected. Potential vessel routes between identified shoals were examined and a cruise plan developed. The following nine shoals were selected for biological assessment: Barracouta Shoal East, Barracouta Shoal West, Echuca Shoal, Eugene McDermott Shoal, Goeree Shoal, Heywood Shoal, Shoal 25(12 30.914S, 124 10.399E), Vulcan Shoal and Wave Governor Bank.

After GIS route planning analysis and calculation of time per shoal needed to complete an adequate environmental assessment, it was decided to split the cruise into two legs (Broome to Broome and Broome to Exmouth) to allow vessel provisioning and a crew change. In both legs, the shoals were examined using a combination of Multibeam Echosounder (MBES) operations, Towed Video, Baited Remote Underwater Video Stations (BRUVS) and Sediment Hydrocarbon sampling, utilising 24 hour ship operation with multibeam being conducted between 6pm and 6am.

Based on limited preliminary bathymetric data an additional site, Shoal 33(12 36.122S, 124 22.250E), was highlighted for investigation. After exploratory surveys during the cruise using multibeam and towed video during Trip 5306 it was found to be an elongated mound on the edge of a ridge and not a shoal with a diverse benthic cover. This location was deemed not suitable for further biological assessment.

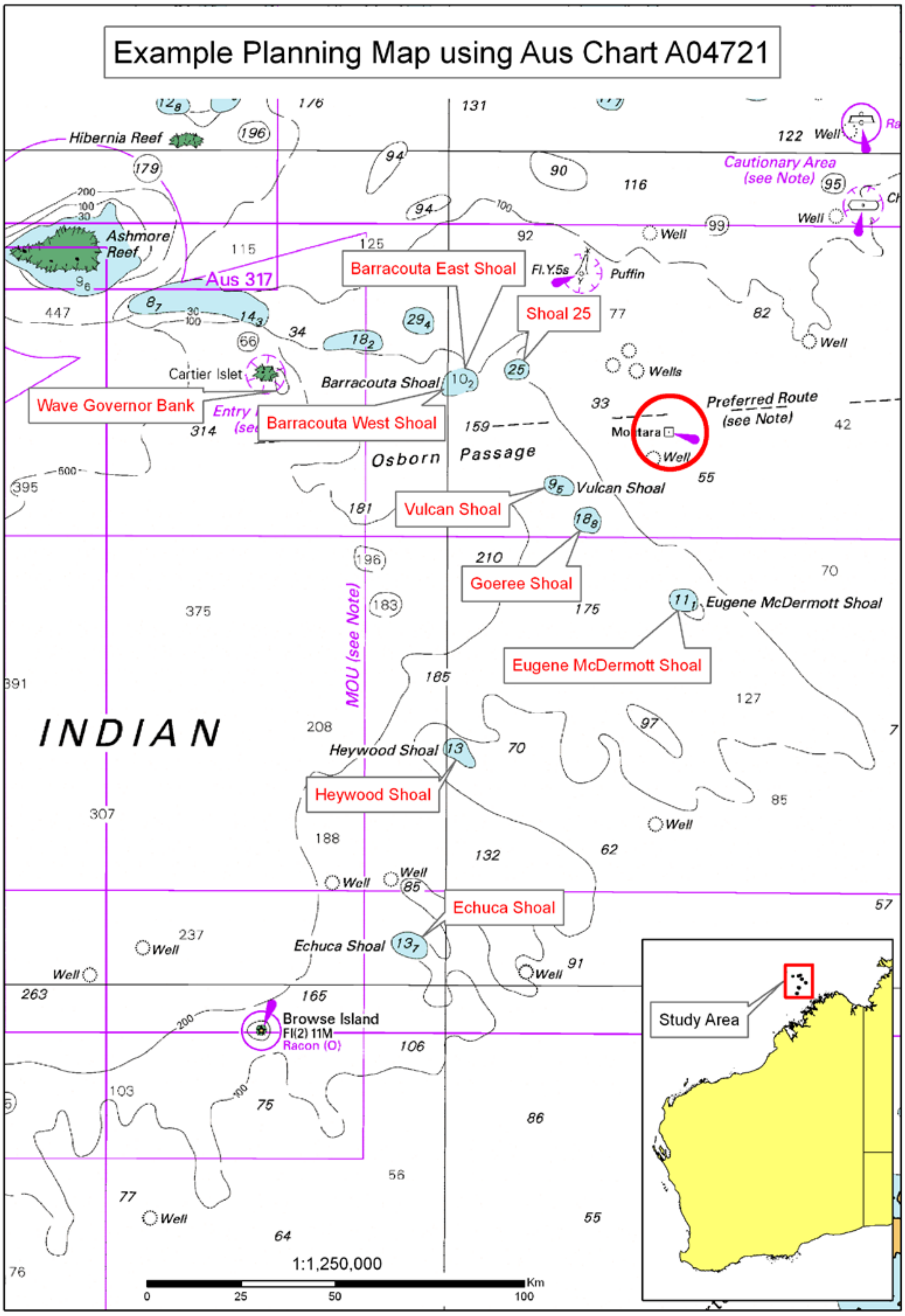

Figure 1.3. Major shoal features adjacent to the Montara well head (red circle) identified from Australian Hydrographic charts. All shoals, with the exception of Shoal 25, have formal names listed on the chart and these have been used in this report (Named in red above.).

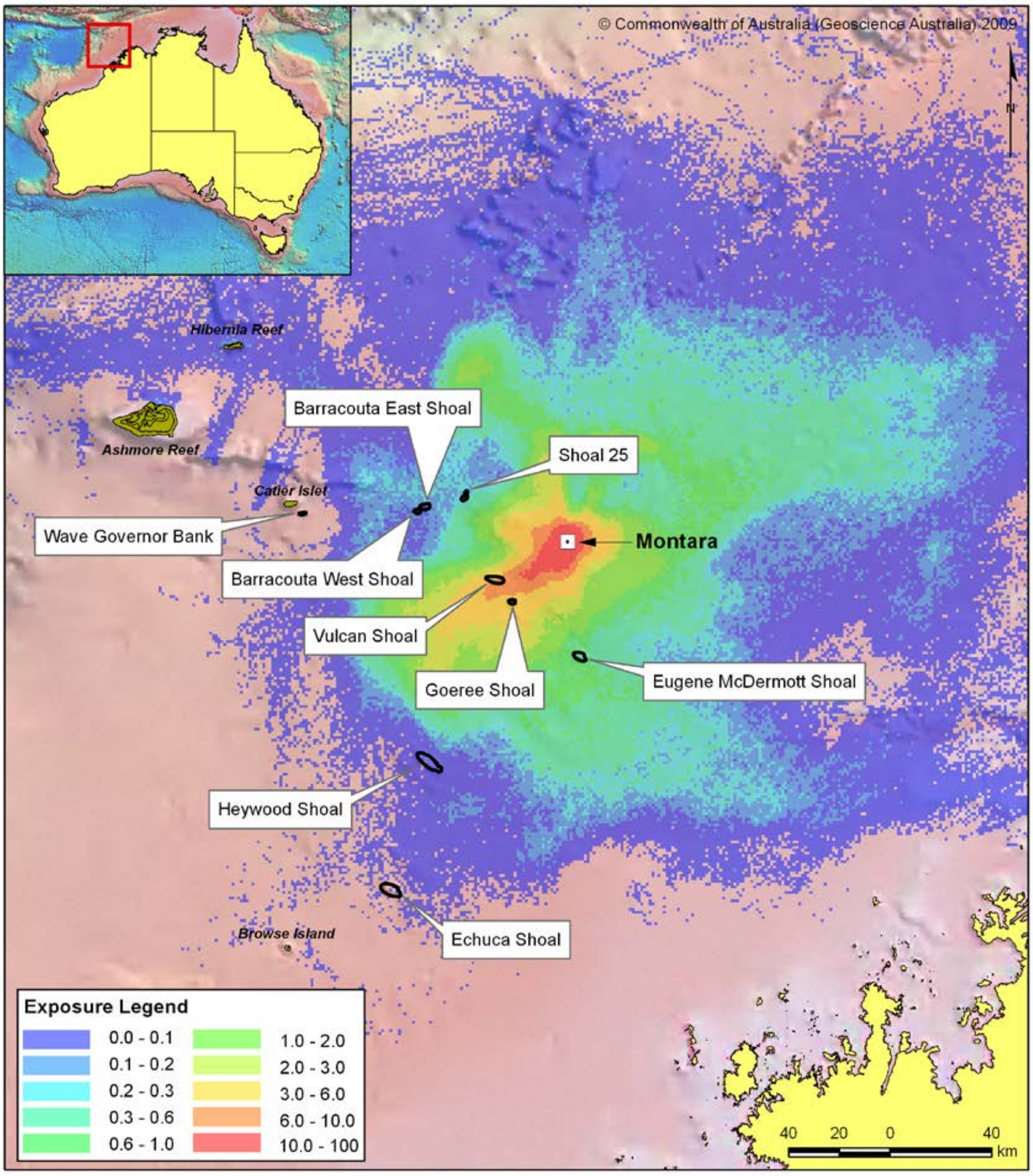

Figure 1.4. Location of the nine shoals selected for the 2011 survey, in relation to the modelled relative exposure to surface hydrocarbons from the Montara oil slick. Image of the spill developed by Asia-Pacific ASA (2010) in another of the independent studies triggered under the monitoring plan developed by the company and DSEWPaC and released by the agency. Relative surface oil exposure map representing all known (99.99%) and estimated occurrences of visible surface oil associated with the Montara Incident. It is important to note that the area shown does not represent the extent of any oil slick observed at any time during the uncontrolled release incident. This represents a summation of the area within isolated patches of oil and wax were observed by aerial or satellite observations and oil spill trajectory modelling. This model has a greater spatial extent compared to the 2010 report (Figure 1.1) due to inclusion of 99.99% of occurrence data, rather than 99.9% The map areas in purple show broader coverage of the lowest threshold, the dark blue extents are characterised by one off occurrences of highly weathered oil with durations of less than 2 hours in any one location (often associated with fast moving current regimes).

Table 1.1. Shoals used for the current surveys. A total of nine shoals were selected using the available chart information in combination with the modelled surface oil exposure models to generate a set of high, medium and low exposure locations.

Shoal	mean Lat	mean Long	Nominal mean depth	dist from uncontrolled release (km)	bearing	Relative impact category (Sea Surface Exposure)
Barracouta East	-12.5456	124.0336	26.8	56.56	284.47	Low
Barracouta West	-12.5612	124.0067	33.5	59.07	281.98	Low
Echuca	-13.9028	123.9071	26.1	153.21	206.37	Low
Eugene McDermott	-13.0754	124.5828	37.5	44.99	174.40	Medium
Goeree	-12.8829	124.3427	35.5	31.65	222.33	High
Heywood	-13.453	124.0474	33.3	101.78	211.62	Low
Shoal 25	-12.5152	124.1733	36.1	43.43	293.72	Medium
Vulcan	-12.8029	124.2816	29.7	31.42	242.42	High
Wave Governor Bank	-12.5702	123.5983	44.6	102.79	276.26	Low

The initial group of eight shoals chosen for the survey were located at various distances and directions from the Montara well head platform to provide a gradient of shoals in relation to the modelled surface exposure map (Table 1.1; Figure 1.3) The four shoals closest to the well head platform, regardless of direction, were most frequently under the surface slick and fell into the medium and high relative impact categories. The remaining five shoals were positioned approximately 55-155 km from the uncontrolled release source and were all ranked as low exposure shoals for the purposes of comparison.

Initial multibeam survey showed that Barracouta shoal (Figure 1.3) was actually comprised of two separate and distinct shoals with a deep channel (~212 m depth) running in between them. Since the two shoals were distinct - as opposed to a single shoal with a common base but two peaks on the east and west sides, Barracouta shoal was divided into Barracouta 'East' and Barracouta 'West' (Table 1.1) and separate surveys were conducted on each of the two shoals. With this sub-division, a total of 9 banks and shoals were surveyed during the 34 day cruise, including an un-named shoal ~45 km NW of the Montara well head platform (referred to as Shoal 25 in Figure 1.3).

The surveys were conducted from the RV Solander on AIMS cruise number 5306, which departed Broome 15 March, 2011 and returned to Exmouth 17 April, 2011, with a break between legs on 1 April, 2011 in Broome. On both legs, banks and shoals were examined using a combination of Multibeam Echosounder (MBES) operations, Towed Video, Baited Remote Underwater Video Stations [BRUVS™] and Sediment Hydrocarbon sampling. Multibeam Echosounder (MBES) operations were conducted by Fugro Survey Pty Ltd under a sub-contract to AIMS.

1.4 References

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2. Sediment Hydrocarbon Analyses

2.1 Introduction

To estimate the potential exposure to oil, sediment samples were examined around nine banks and shoals close to the Montara WHP in the Timor Sea. Collection of samples occurred at the same time as the habitat mapping surveys (Section 3) and Baited Remote Underwater Video Stations (BRUVS™) (Section 4) surveys, and was intended to assist in the interpretation of the results. AIMS proposed collecting 50 sediment samples and analysing these using UVF fluorescence techniques, with more detailed analyses of 5 (i.e. 10%) of the samples by GC/MS (gas chromatography-mass spectrometry). Field work was conducted in March and April 2011 and ultimately involved the collection of >200 sediment samples of which 57 samples were analysed using UV/F fluorescence techniques, and 33 (i.e. ~60%) of these were subsequently analysed using GC-MS.

2.2 Methods

2.2.1 Site selection

Between 17 March and 14 April 2011, a total of 203 sediment samples were collected using a Smith McIntyre bottom grab sampler from 57 locations in the Timor Sea ranging in distance from 2.5 km to 155 km from the Montara well head platform (WHP) (Table 2.1; Figure 2.1A, B, C). Samples were collected on approximately cardinal points 1-2 km away from each of the shoals except the Wave Governor bank south of Cartier islet which proved too coarse to allow successful operation of the grab.

Table 2.1. Sampling locations. Where UV/F = Ultraviolet Fluorescence (UV/F) analysis and GC-MS represent gas chromatography-mass spectrometry. Note no sediment samples could be collected around Wave Governor Bank, as the sediments were too coarse to allow operation of the grab. Numbers include duplicate samples.

	Location	Depth range (m)	Sampling Location (n)	Samples collected[2] (n)	Samples analysed (UV/F)	Samples analysed (GC-MS)
1	1-2 km North, East, South and West of each of 8 shoals/banks (Eugene McDermott, Goeree, Vulcan, Shoal 25, Barracouta (East) and Barracouta (West), Echuca and Heywood shoal [1]	86-204	32	112	32	10
2	the top of three shoals - Barracouta (East), Goeree and Vulcan	36-55	6	16	6	2
3	at the Cornea Seeps	89-106	4	15	8	3
4	2.5-3 km North, East, South and West of the Montara WHP	75-83	4	16	4	4
5	along a 30 km SW transect (bearing 230°) from 6.5 km SW of the Montara WHP	82-174	11	44	16	14
		Total:	57	203	66	33

2.2.2 Sample collection/handling

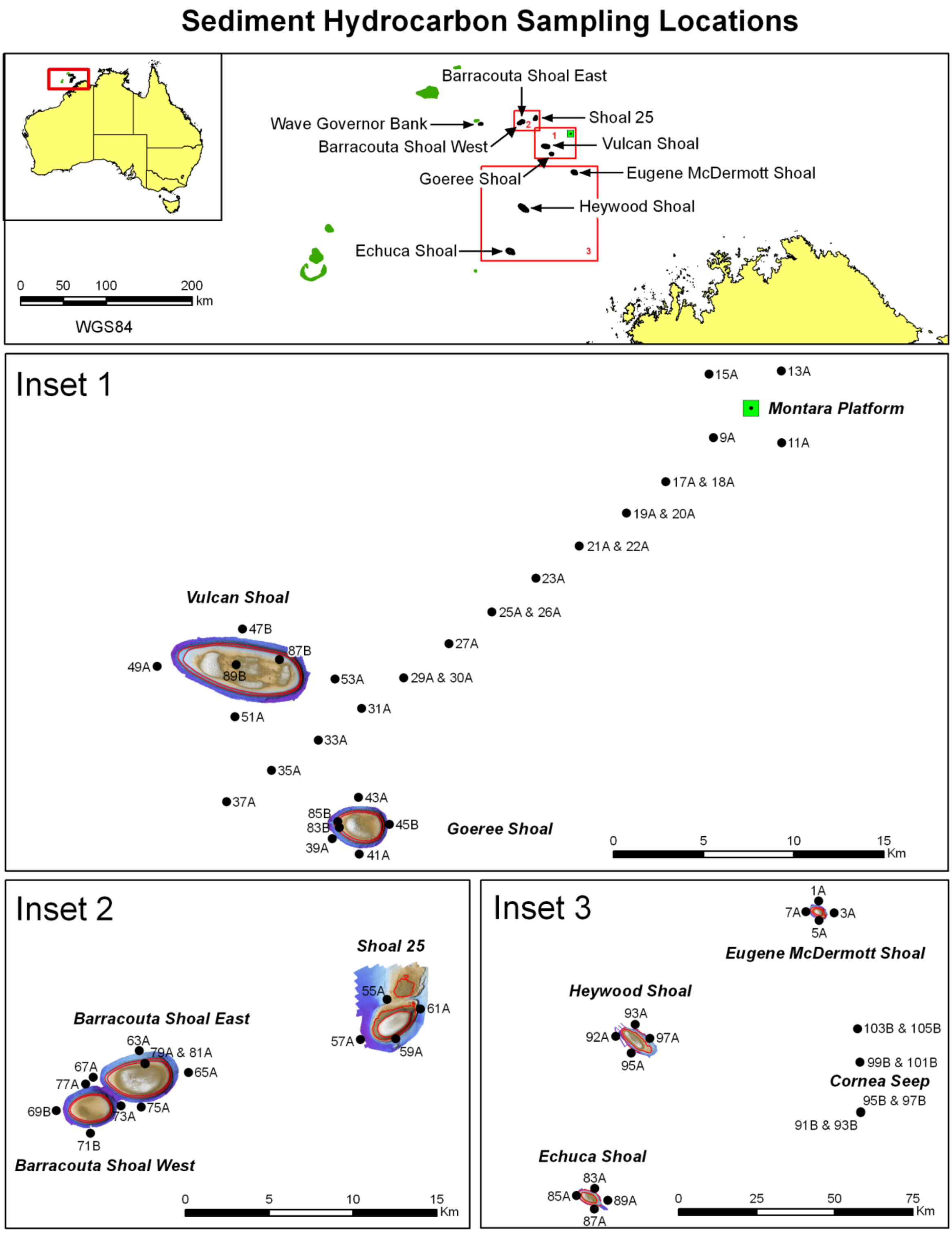

Figure 2.1A. Location map showing the sediment sampling strategy around the perimeter (N, E, S, W) of 8 banks/shoals (depth: 87-204 m), around the Montara WHP (depth: 75-83 m), around the Cornea Seeps (depth: 89-109 m), on the tops (<55 m depth) of 3 shoals (Barracouta (East), Goeree and Vulcan) and along a SW transect (bearing 230°) from ~6.5 km from the Montara WHP (depth: 82 m) to a point 36 km SW of the platform. Note: no sediment samples could be collected around Wave Governor Bank (see Table 2.1).

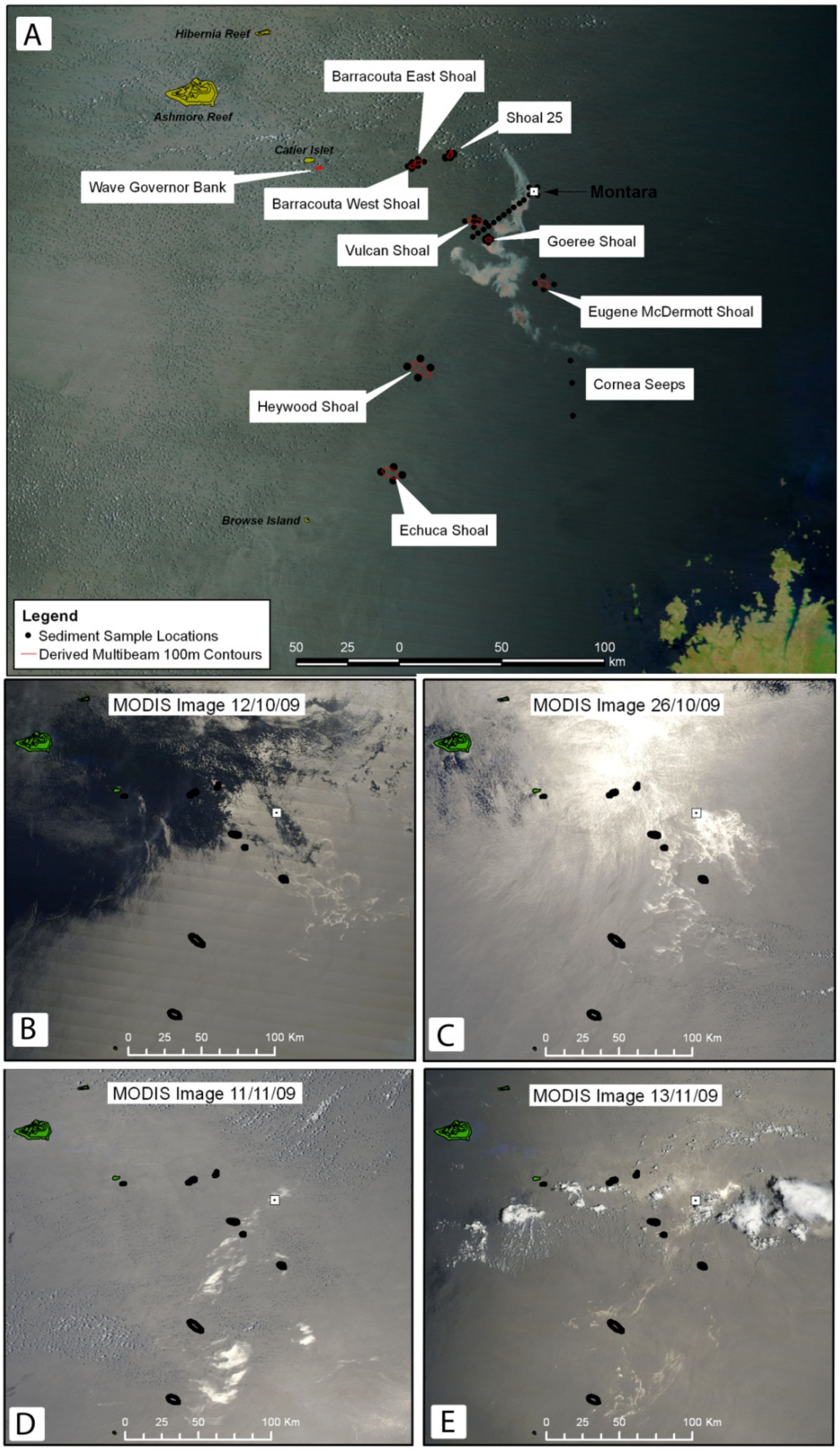

Figure 2.1B. Geo-rectified satellite image (The Moderate Resolution Imaging Spectroradiometer, MODIS) of the study area taken on 5 occasions from 12 October to 13 November (2009) showing surface slicks relative to the sediment sampling locations. Credit: NASA/GSFC, Rapid Response.
(A) http://lance-modis.eosdis.nasa.gov/imagery/subsets/?project=other&subset=Australia1.2009292.terra.721.250m
(B) http://lance-modis.eosdis.nasa.gov/imagery/subsets/?project=other&subset=Australia1.2009285.terra.250m
(C) http://lance-modis.eosdis.nasa.gov/imagery/subsets/?project=other&subset=Australia1.2009299.aqua.250m
(D) http://lance-modis.eosdis.nasa.gov/imagery/subsets/?project=other&subset=Australia1.20092315.aqua.250m
(E) http://lance-modis.eosdis.nasa.gov/imagery/subsets/?project=other&subset=Australia1.2009317.terra.250m

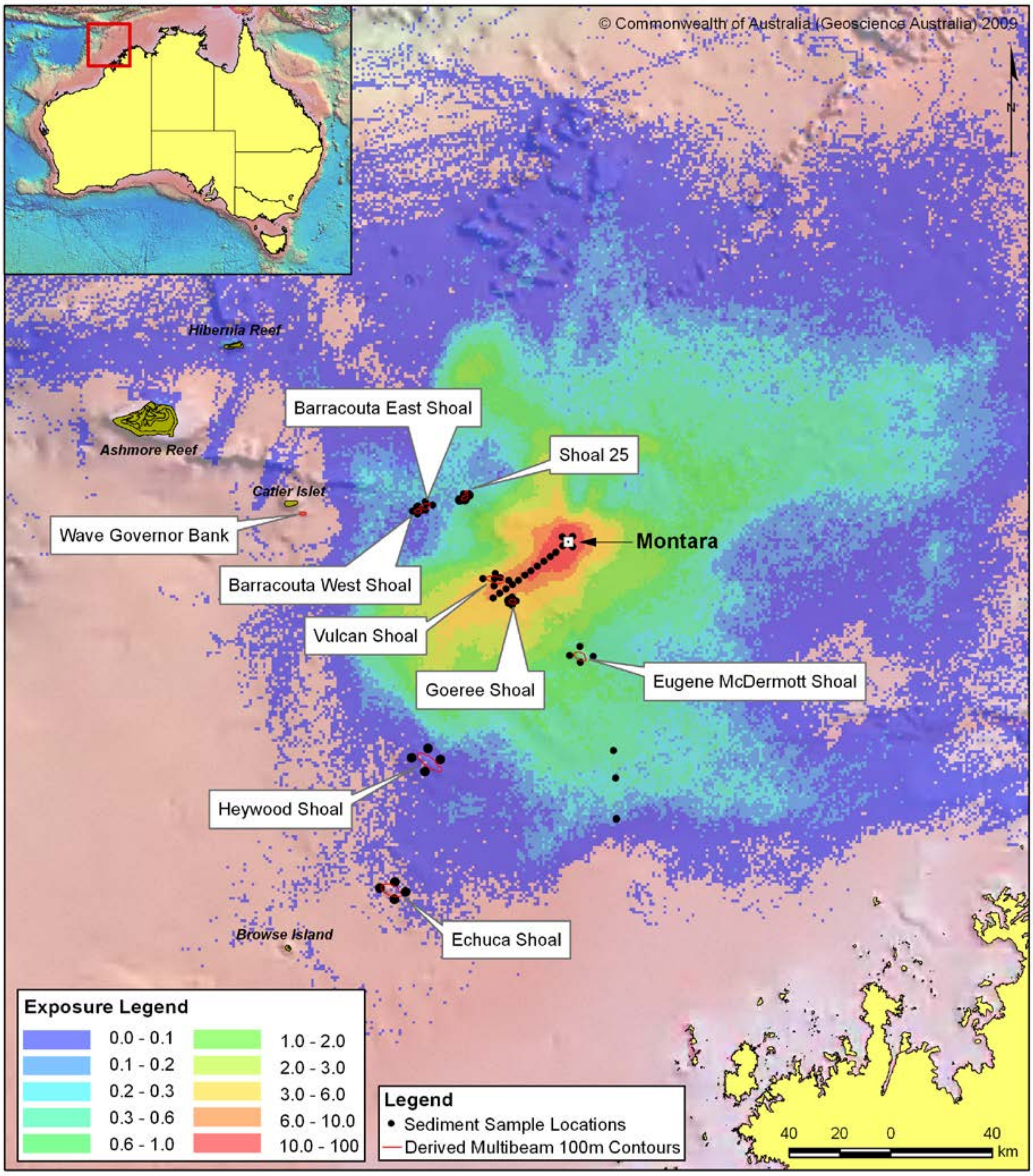

Figure 2.1C. Relative surface oil exposure showing all known and estimated occurrences of visible surface oil associated with the Montara Incident. It is important to note that the area shown does not represent the extent of any oil slick observed at any time during the uncontrolled release incident. It is a summation of the area within isolated patches of oil and wax that were observed by aerial or satellite observations and oil spill trajectory modelling. The dark blue extents are characterised by one off occurrences of highly weathered oil with durations of less than 2 hours in any one location, often associated with fast moving current regimes. The colour legend depicts the % of occurrences (per 1.1 × 1.1 km cells) and uses a logarithmic scale. Source: Figure 25 of the Montara Well Release Monitoring Study S7.1 Oil Fate and Effects Assessment Final report 4th October 2010 (Asia-Pacific ASA. 2010a). Superimposed on the exposure map is the sediment sampling strategy in deeper water around the perimeter (N, E, S, W) of 8 banks/shoals, around the Montara WHP, around the Cornea Seeps, on the tops (<55 m depth) of 3 shoals (Barracouta (East), Goeree and Vulcan) and along a 30 km SW transect (bearing 230°) from 6.5 km from the Montara WHP to a point 36 km SW of the platform. Note: no sediment samples could be collected around Wave Governor Bank (see Table 2.1).

The tops of the shoals also proved to be very gravelly (i.e. grain size >2 mm) for sampling and despite multiple attempts only a few samples (n=6) could be retrieved (at Barracouta East, Goeree and Vulcan shoal). Samples were collected from an area of known hydrocarbon seepage on the Yampi shelf in the vicinity of the Cornea oil and gas field (Cornea Seeps, see Rollet et al. 2006; Burns et al. 2010) and on approximately cardinal points 2.5-3 km away from the Montara WHP, and outside the 500 m exclusion zone around the platform. Samples were also collected along a ~30 km SW transect (bearing 230°) from 6.5 km from the Montara WHP to a point 36 km SW of the platform ending equidistant from Goeree and Vulcan shoal (Figure 2.1A).

The grab sampler was cleaned with brushes and water in between stations. No surface slicks were visible during sampling. During sampling from the grab, water was first siphoned away exposing the sediment and the upper (surficial) sediments. Samples were taken from the middle of the grab, away from the metal sides. The surface 1 cm was removed using a stainless steel spatula and placed into a glass jar which was sealed with pre-combusted aluminium foil under the lids. The lower 1-3 cm layer was also sampled into a separate glass jar at the majority of locations. Where possible, duplicate samples, labelled 'A' and 'B' were taken at each sampling location. All samples were shipped frozen to the Geochemistry Laboratory at AIMS in Townsville for hydrocarbon analysis. In general the 'A' samples were selected for analysis although occasionally the duplicate 'B' sample was analysed. All glassware, Teflon and stainless steel implements were thoroughly cleaned for trace analysis and rinsed in GCMS grade solvents.

A remaining bulk sediment sample from each grab was also collected for GeoScience Australia's Marine Sediments (MARS) database. The sediment classification system of (Folk 1954) was used to present information on grain size distribution using a triangular diagram divided into textural groups based on the percentages of gravel (>2 mm), sand (<2 mm and >63 µm) and mud (<63 µm).

2.2.3 Laboratory analyses

A total of 66 samples were selected for extraction and by scanning with Ultraviolet Fluorescence (UV/F) analysis (UNEP, 1992). Sediments were defrosted in batches of 19 by placing in a refrigerator overnight. For each sample, seawater overlaying sediment was pipetted into a glass tube with a Teflon lined screw cap. Two mL of extraction solvent was added to this water and used to extract any hydrocarbons that may have been dissolved off the sediments during freezing.

Sandy to muddy sediments in the jars were thoroughly stirred with a stainless steel spatula and sub-sampled for wet to dry weight determinations. The remainder (20 to 30 g wet) was scraped into a 250 mL beaker, weighed and had approximately two to three times the wet weight of pre-combusted powdered sodium sulfate added to bind water. This mixture was thoroughly stirred to make sure the salt was evenly blended with the sediment. The sediment mixture was then scrapped into a 90 mL Teflon bottle. The solvent from the water extraction was also added to the Teflon bottle. Then 35 mL of 10% methanol (MeOH) in dichloromethane (DCM) was added to start the extraction. Surrogate standards (OTP or orthoterphenyl and C22:1) were added to track recovery. OTP is the only aromatic hydrocarbon that does not fluoresce. Thus it is an ideal surrogate standard. Samples would be calculated against the recovery of OTP throughout the procedure. Bottles were sealed tightly and shaken vigorously to disperse the solvent with the sediment. Bottles were then placed in a plastic tray with water in the bottom and the probe of a sonicator lowered into the water. Bottles were sonicated for an average of 40 minutes. First extracts were allowed to soak overnight in a refrigerator. Extracts were then filtered through a 10 mL glass syringe plugged with pre-cleaned cotton and packed with about 3 cm of powdered sodium sulfate in a vacuum filter box into a 250 mL round bottom glass flask. Each sample had its own syringe filter. Second and third extractions were done by adding 35 mL of DCM and repeating the sonication and filtration. The three extracts were combined and reduced in volume to about 2 mL using a chilled (1°C) rotary evaporator.

Reduced extracts were transferred to Teflon lined screw cap tubes and carefully reduced to near dry using pure nitrogen gas. They were then taken up in 0.2 mL hexane and cleaned on a mini column of 1 g Al_2O_3 to remove interfering plant pigments. Hydrocarbons were eluted off the alumina with 2 mL hexane followed by 2 mL DCM. Extracts were then adjusted to 1 mL for UV/F analysis. Complete procedural blanks were obtained by extraction of 30 g of pre-combusted sodium sulfate.

A sample of NAPL (non-aqueous phase liquid) from an oil/water sample recovered by fishermen from one of the Montara uncontrolled release was given to WA Fisheries. This was given to Trevor Bastow at CSIRO for confirmation as water washed Montara crude and then on to the AIMS lab as a reference sample. The oil was made up to concentrations of 0.2 mg/mL for UV/F analysis and 1.1 mg/mL for the GCMS. A six point calibration curve was constructed from the oil standard. Samples were analysed by putting increasing amounts of samples (10 to 50 µL additions) to 1 mL of hexane in the quartz cell. This method ensures the measurements do not suffer inner filter effects. Each extract was examined at wavelengths of 280 nm excitation / 327 nm emission and 310 nm ex / 360 nm em.

Samples were calculated at excitation/emission wavelengths of 280nm/327nm and compared to a five point calibration using the NAPL standard. They were then compared to the standard curve based on the higher wavelength set. Each extract was also synchronously scanned with excitation and emission monochrometers set 25 nm apart. Spectra were obtained from 280 to 500 nm emission.

The Montara oil is light-weight crude and its UV/F maximum was in the lower wavelength range. However as the oil in sediments weathers, the lower molecular weight compounds are lost to dissolution. This lowers the emission at the lower wavelength and increases the emission at the higher wavelength. The amounts of oil listed in the table are based on the sum of oil calculated at both wavelength sets and includes the lower and higher molecular weight aromatic hydrocarbons. Amounts are expressed as µg oil per g dry weight.

Samples were judged positive when they had at least three times the blank values at both wavelength sets. Samples (n=32) that had detectable oil by UV/F analysis and a few that were blank were selected for gas chromatography-mass spectrometry (GCMS) analysis.

The selected samples were carefully reduced to 100 µL and transferred to a GCMS vial with a 150 µL glass liner. Internal standards were added and the samples were then analysed for their aromatic hydrocarbons using an acquisition program designed for SIM acquisition of 293 aromatic hydrocarbons and standards. Total hydrocarbons and alkanes were measured by a second injection using a SCAN/SIM program.

These GCMS analyses are the same methods as used in Burns et al., (2010). Quality assurance procedures included complete procedural blanks accompanying every batch of 19 samples. The use of surrogate and internal standards in both samples and blanks facilitated calculating overall recoveries in the analytical procedures and instrumental analysis respectively. PAH and biomarker standards were purchased from reputable suppliers and made up to allow five point calibrations. Recoveries of the OTP surrogate standard averaged about 80% after the UVF analysis. GCMS analyses were adjusted for these recoveries.

Total organic carbon and nitrogen were determined in subsamples of dried ground sediments using high temperature combustion analysis on a Shimadzu 5000A TOC instrument with the solid sample attachment and a TNM-1 attachment for nitrogen. Samples were pre-acidified to remove carbonates.

2.3 Results and Discussion

2.3.1 Sediment characteristics

The surficial (0-1 cm) and deeper (1-2 cm) sediments collected from 75-204 m water depth around the perimeter of the shoals were generally gravelly sands (gS), sands (S), and gravelly muddy sands (gmS) according to the (Folk 1954) textural classification scheme (Figure 2.2 and Table 2.3). The samples collected from around Echuca Shoal and Cornea Seeps had a lower gravel content and higher mud content and were classified as either gravelly muddy sands (gmS) or muddy sands (mS) (Figure 2.2). Three of the samples around Eugene McDermott shoal and one of the samples around Echuca Shoal were notably different from the other sediment samples collected, having much higher mud content and were classified as sandy Mud (sM).

Samples collected from the tops of the shoals (21-55 m) were either gravelly sands (gS), sandy gravel or in the case of the samples collected from the top of Goeree, gravel (G).

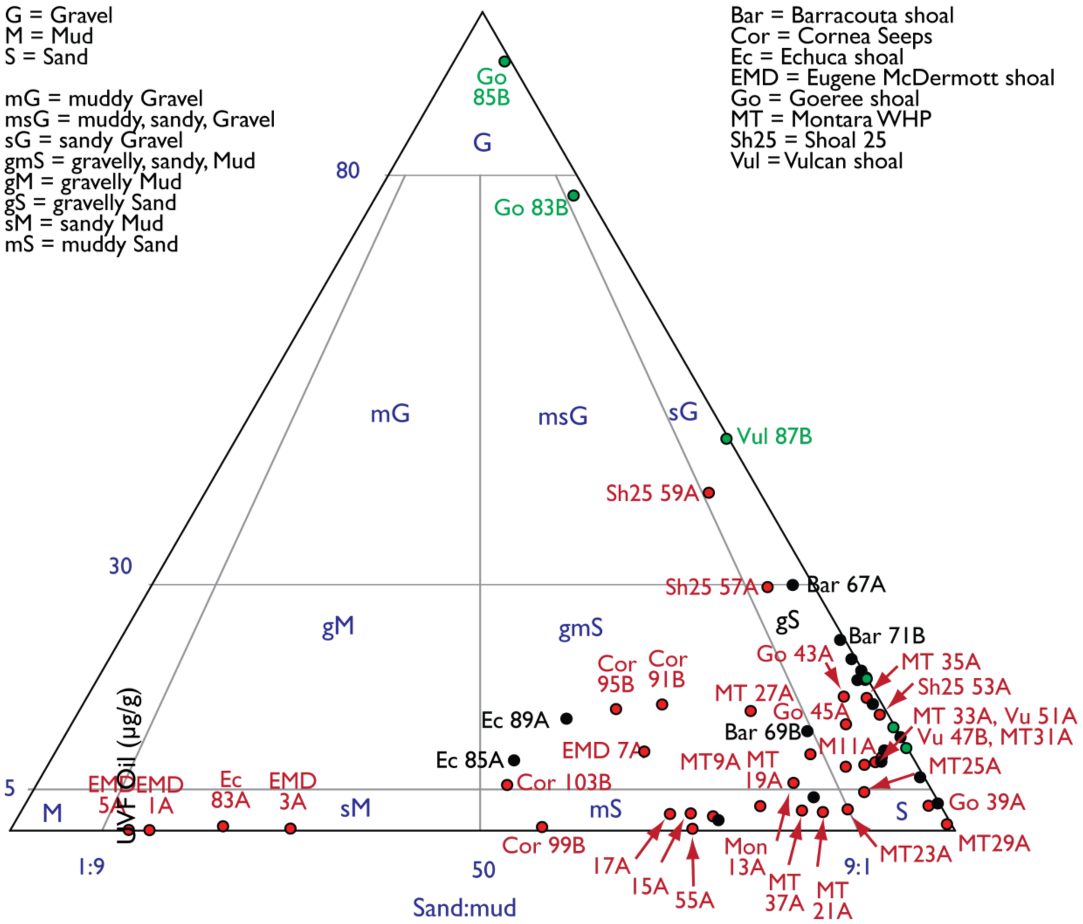

Figure 2.2. Triangular diagram showing the grain size analysis of sediment collected from on and around the banks and shoals, Montara platform and Cornea Seep (See Figure 2.1A, B). Sites in Red are samples where hydrocarbons were detected by UV/F analyses and which were subsequently analysed by GCMS (see text). Green samples were collected from the tops of three shoals (see Table 2.1).

2.3.2 UV/F Analyses

The results of UV/F analysis of the 66 extracts are shown in Table 2.2. Amounts of oil calculated at the two wavelengths are combined as the wavelengths measure low and high molecular weight aromatics and the oil is a mixture of both. Concentrations in whole (un-sieved) surficial (top 1 cm) sediment samples ranged from non detectable (nd) (< ~0.03 µg/g) to 2.2 µg/g 1 km N of Eugene McDermott shoal. Oil in the sandy sediments around the Montara well-head platform ranged from 0.26 to 0.72 µg/g (mean ± SD: 0.41 ± 0.21, n = 4) similar to values in the muddy sediments in the positive control area of the natural gas and oil seeps at Cornea (Range: 0.31 to 1.17 µg/g, mean ± SD: 0.54 ± 0.43, n = 4).

All surficial sediment around Eugene McDermott (range 0.57-2.20 µg/g) contained oil concentrations above the method detection limit. Oil concentrations above the detection limits were also recorded at three of the four samples at each of Goeree shoal (range: 0.13-0.22 µg/g), Vulcan shoal (0.17 – 0.41 µg/g), and Shoal 25 (0.15-0.27 µg/g). Only one sediment sample at Echuca had hydrocarbon levels above the detection limit and no oil was recorded at Barracouta Shoal (East), Barracouta shoal (West), or at Heyward Shoal (Table 2.2).

No sediment samples collected in shallower water (<55 m depth) from the tops of Barracouta East, Goeree and Vulcan shoal) had oil concentrations above the detection limits (Table 2.2). All samples around the Cornea seeps had detectable hydrocarbon concentrations, with the highest value of 1.17 µg/g sample 103B found in a gravelly, muddy, sand sample (Figure 2.2). Around the Montara WHP concentrations ranged from 0.3-0.72 µg/g in predominantly sandy samples, and hydrocarbons were also detected in all samples collected on the transect running from 6.5 Km SW of the platform to ~36 km SW of the WHP and ending between Goeree and Vulcan shoals (see Figure 2.1 A, B, C). Hydrocarbons were also detected in deeper sediments (1-2 cm deep) in three of the five sediment samples collected along the transect and in two of the four deeper samples at the Cornea Seeps (Table 2.2).

2.3.3 GCMS Analyses

GCMS analyses was conducted on 50% (n=33) of the sediment samples previously identified as containing oil based on the UV/F analyses, and the summary statistics are shown in Table 2.3 where 'Oil PAHs' are the sums (∑) of parent and alkylated aromatic hydrocarbons in the naphthalene/biphenyl, phenanthrene/anthracene, dibenzothiphene, pyrene/fluoranthene, and chrysene/benzanthracene series and 'Combustion PAHs' are ∑ benzo(bk)fluoranthene, benzo(a,e)pyrene, indenopyrene, dibenzanthracene and benzo(ghi)perylene.

Values of total hydrocarbons (THC) ranged from 10.4 µg/g at Eugene McDermott shoal (North) to 1.2 µg/g at Barracouta shoal (East) and the sum of oil PAHs ranged from 31.0 ng/g at Eugene McDermott Shoal (North) to 0.29 ng/g at Echuca Shoal (West)(Table 2.3). Significant amounts of the THC were unresolved complex material (UCM) typical of residual petroleum (Table 2.3, see also Figure 2.4).

Tables 2.4 and 2.5 contain the summary PAH and oil biomarker data calculated for the 33 sediment extracts.

Many of the extracts contained PAHs, sterane and triterpane biomarkers expected for a degraded crude oil. Within each PAH group the higher molecular weight alkyl substituted compounds predominated. The presence of flourenone is a photo-oxidation marker for petroleum (Ehrhardt and Burns, 1993) suggesting the oil had undergone significant amount of photo oxidation before being incorporated into the sediments.

Reconstructed ion chromatographs (RICs) of samples overlain with the analytical blank as reference are shown for the sediments at Eugene Mc Dermott shoal (N Sample 1A, Figure 2.4 A) and for the Cornea seep area (Sample 103B, Figure 2.4 B respectively).

The samples contained a pattern showing degraded crude oil. Both sediments had similar patterns with high molecular weight alkanes visible over the unresolved complex mixture (UCM) of hydrocarbons typical of a degraded oil pattern. However, the Cornea seep sediments showed a recent input of high molecular weight alkanes probably from the active seep in the area. All the sediments showed specific phytoplankton, alkenones and other biogenic hydrocarbon peaks. These biogenics were not included in the total hydrocarbon analysis.

To facilitate the interpretation of these patterns, and to illustrate the partitioning of hydrocarbons in the environment, Figure 2.4 C, D and E show scans of samples from the Cornea seep collected in 2005 (see Burns et al. 2010) from the Cornea surface microlayer, in particles collected by sediment traps suspended in the seep area, and in the surface sediments in the seep area, respectively. Some of the peaks are identified in these figures.

In Figure 2.4 C, the surface slick sample, shows a relatively fresh crude oil with alkanes visible over an unresolved complex mixture of hydrocarbons. The oil has been severely weathered by dissolution and evaporation processes. Few biogenic hydrocarbons are visible in the image. Figure 2.4 D shows the crude oil pattern with several biogenic alkanes in the C14 to C21 range and significant concentrations of the low molecular weight aromatic compounds. Figure 2.4 E is typical of sediments from the Cornea seep area. There was a degraded petroleum pattern with even more biogenic hydrocarbons, some of which are identified in the image such as wax esters, alkenes and highly branched isoprenoid hydrocarbons sourced from algae.

The diploptene is the hydrocarbon moiety derived from the sterol diploterol found in sulphate reducing methanotrophic bacteria (Hinrichs 2001; Hinrichs et al, 2003). Diploptene has been used by geochemists to trace oil and gas seeps in the geological record (Uchida et al., 2004). There were highly significant correlations between the amounts of oil determined as total hydrocarbons and by the sum of the oil PAHs and with the biomarker diplotene in the extracts (Figure 2.3A-C). The hydrocarbon biomarker Tables 2.5A and B show that the concentrations of diploptene in the sediment samples were orders of magnitude higher than any of the triterpane of sterane oil biomarkers. Thus, it is not possible to source the oil in the sediments to the original oil spilled or seeped. Burns et al. (2010) based source identification to the Cornea oil on the hydrocarbons found in sediment traps which were much less degraded.

Burns et al (2010) analyzed sediments from the Cornea area. Table 2.6 gives a comparison of concentrations in the Eugene McDermott Shoals sediments and the Cornea sediment samples from the two sampling times. The concentrations of petroleum in the McDermott sediments were twice as much as at the natural seep site at Cornea on both occasions.

The traces of oil in shoals and reefs sediments away from where the surface oil slicks had been could be from other background sources such as fishing boats and other oil industry activities in the region.

Table 2.2. Petroleum oil content (µg/g) based on UV/F analysis (sum of two wavelength measurements) in 66 sediment samples collected during March and April 2011 – see Table 2.1 and Figure 2.1 for sampling. Bold samples are those selected for GCMS analysis. Where E.Mc.D = Eugene McDermott shoal and Barra. = Barracouta shoal. Samples were calculated at the two wavelengths which were indicative of low molecular weight and higher molecular weight aromatic hydrocarbons. Interfering pigments were previously removed with Al_2O_3. Linear regressions were made at both set of wavelengths from the Montara NAPL oil.

No.	Site Name	GA	Gravel %	Sand %	Mud %	Latitude (S)	Longitude (E)	Depth (m)	Dist. (Km)	280/327 µg/g	310/360 µg/g	Oil (µg/g)
(A) Surficial (0-1 cm sediment depth) samples around Shoal perimeter												
1A	**E.McD. (N)**	**1**	0.0	14.8	85.2	13.043930	124.582907	146	41.4	0.49	1.71	**2.20**
3A	**E.McD. (E)**	**2**	0.2	29.6	70.2	13.079047	124.629475	147	46.0	0.15	0.66	**0.81**
5A	**E.McD. (S)**	**3**	0.0	12.6	87.4	13.100448	124.584273	155	47.6	0.24	0.75	**0.99**
7A	**E.McD. (W)**	**4**	9.6	62.4	28.1	13.075592	124.546283	156	44.6	0.14	0.43	**0.57**
39A	Goeree (W)	20	3.0	95.7	1.3	12.889248	124.328237	180	33.3	nd	0.21	**0.21**
41A	Goeree (S)	21	15.4	83.6	1.0	12.897072	124.342115	180	32.9	nd	nd	**nd**
43A	Goeree (N)	22	16.3	80.1	3.6	12.868525	124.341513	178	30.7	nd	0.13	**0.13**
45B	Goeree (E)	23	12.9	82.0	5.1	12.882067	124.357360	178	31.0	nd	0.22	**0.22**
47B	**Vulcan (N)**	**24**	8.3	87.4	4.3	12.784320	124.281900	177	30.8	0.14	0.27	**0.41**
49A	Vulcan (W)	25	18.3	81.3	0.3	12.803335	124.238323	196	35.9	nd	nd	**nd**
51A	**Vulcan (S)**	**26**	8.0	86.5	5.6	12.828413	124.278238	176	33.4	0.14	0.37	**0.51**
53A	Vulcan (E)	27	14.1	85.0	0.9	12.809248	124.329178	180	27.6	nd	0.17	**0.17**
55A	Shoal 25 (N)	28	0.1	72.2	27.7	12.502183	124.169543	120	44.5	nd	0.27	**0.27**
57A	Shoal 25 (W)	29	29.7	65.4	5.0	12.523802	124.155050	155	45.1	nd	0.24	**0.24**
59A	Shoal 25 (S)	30	41.2	53.4	5.4	12.523285	124.174407	131	43.1	nd	0.15	**0.15**
61A	Shoal 25 (E)	31	1.2	74.4	24.4	12.507225	124.187930	135	42.5	nd	nd	**nd**
63A	Barra. East (N)	32	18.6	81.3	0.0	12.530337	124.033582	153	57.3	nd	nd	**nd**
65A	**Barra. East (E)**	**33**	19.5	80.4	0.1	12.541953	124.060533	174	54.2	nd	nd	**nd**
67A	Barra. East (W)	34	29.9	67.9	2.2	12.544705	124.008352	184	59.6	nd	nd	**nd**
69B	Barra. West (W)	35	12.1	78.4	9.6	12.562968	123.987983	172	61.3	nd	nd	**nd**
71B	Barra. West (S)	36	23.2	76.3	0.5	12.575088	124.006917	204	59.0	nd	nd	**nd**
73A	Barra. West (E)	37	3.3	96.6	0.2	12.560093	124.023513	184	57.6	nd	nd	**nd**
75A	Barra. East (S)	38	20.9	78.6	0.5	12.560707	124.034783	193	56.4	nd	nd	**nd**
77A	**Barra. West (N)**	**39**	6.5	93.1	0.4	12.548204	124.004116	184	59.9	nd	nd	**nd**
83A	**Echuca (N)**	**43**	0.5	22.3	77.2	13.878973	123.926402	141	149.2	0.08	0.27	**0.35**
85A	Echuca (W)	**44**	8.5	49.1	42.4	13.899875	123.872020	145	153.9	nd	nd	**nd**
87A	Echuca (S)	45	4.0	83.1	12.9	13.938778	123.924927	130	155.2	nd	nd	**nd**
89A	Echuca (E)	46	13.6	52.1	34.3	13.913170	123.964433	125	150.8	nd	nd	**nd**
92A	Heywood (W)	47	18.3	80.5	1.1	13.438680	123.985867	105	104.0	nd	nd	**nd**
93A	Heywood (N)	48	8.3	88.1	3.6	13.403895	124.043403	105	97.3	nd	nd	**nd**
95A	Heywood (S)	49	9.7	87.7	2.6	13.487427	124.032530	102	105.7	nd	nd	**nd**
97A	Heywood (E)	50	11.4	88.6	0.1	13.443878	124.087813	87	98.5	nd	nd	**nd**
(B) Surficial (0-1 cm sediment depth) samples on tops (i.e. <55 m water depth) of three shoals (0-2 cm)												
79A	Barracouta (East)	41	12.5	87.2	0.2	12.537178	124.036600	36	56.8	nd	nd	**nd**
81A	Barracouta (East)	42	10.0	89.9	0.1	12.537358	124.036778	35	56.8	nd	nd	**nd**
83B	Goeree (SW)	53	77.5	20.9	1.6	12.883622	124.331870	50	32.6	nd	nd	**nd**
85B	Goeree (NW)	54	93.9	5.4	0.7	12.880680	124.330982	55	32.4	nd	nd	**nd**
87B	**Vulcan**	**55**	47.8	51.9	0.3	12.799605	124.300710	30	29.7	nd	nd	**nd**
89B	**Vulcan**	**56**	18.5	81.4	0.1	12.802335	124.278758	21	31.9	nd	nd	**nd**

Table 2.2 continued. Petroleum oil content (µg/g) based on UV/F analysis (sum of two wavelength measurements) in 66 sediment samples collected during March and April 2011 – see Table 2.1 and Figure 2.1 for sampling. Bold samples are those selected for GCMS analysis. Note: Samples were calculated at the two wavelengths which were indicative of low molecular weight and higher molecular weight aromatic hydrocarbons. Interfering pigments were previously removed with Al_2O_3. Linear regressions were made at both set of wavelengths from the Montara NAPL oil.

No.	Site Name	GA	Gravel %	Sand %	Mud %	Latitude (S)	Longitude (E)	Depth (m)	Dist. (Km)	280/327 µg/g	310/360 µg/g	Oil (µg/g)
(C) Surficial (0-1 cm sediment depth) samples around Montara wellhead platform and Cornea seep												
9A	**Montara (W)**	**5**	1.7	73.6	24.7	12.687038	124.521982	83	2.6	0.27	0.45	**0.72**
11A	**Montara (S)**	**6**	9.3	80.1	10.6	12.689453	124.556720	82	2.5	0.15	0.20	**0.35**
13A	**Montara (E)**	**7**	5.8	80.1	14.2	12.653487	124.556460	75	2.7	0.07	0.20	**0.27**
15A	**Montara (N)**	**8**	2.0	71.1	26.9	12.655273	124.519427	82	3.0	0.08	0.22	**0.30**
91B	Cornea Seep	57	15.3	61.4	23.3	13.655282	124.711738	90	110.3	nd	0.22	**0.22**
95B	**Cornea Seep**	**58**	14.8	56.8	28.5	13.652863	124.711642	89	110.3	0.11	0.37	**0.48**
99B	**Cornea Seep**	**59**	0.4	56.1	43.5	13.510232	124.708268	109	94.5	nd	0.31	**0.31**
103B	**Cornea Seep**	**60**	5.5	49.9	44.6	13.412895	124.700795	106	83.7	0.33	0.83	**1.16**
(D) Surficial (0-1 cm sediment depth) samples along the Montara transect												
17A	**Montara Trans.**	**9**	2.0	68.9	29.2	12.709353	124.497693	82	6.3	0.04	0.13	**0.17**
19A	**Montara Trans.**	**10**	2.9	78.0	19.1	12.725150	124.477790	86	9.0	0.06	0.18	**0.24**
21A	**Montara Trans.**	**11**	2.2	85.0	12.9	12.741950	124.453693	89	12.2	0.12	0.32	**0.44**
23A	**Montara Trans.**	**12**	2.5	87.4	10.1	12.758162	124.431590	90	15.2	nd	0.08	**0.08**
25A	**Montara Trans.**	**13**	4.6	88.1	7.3	12.775197	124.409270	97	18.3	0.04	0.11	**0.15**
27A	**Montara Trans.**	**14**	14.5	71.1	14.3	12.791170	124.387400	130	21.3	0.04	0.12	**0.16**
29A	**Montara Trans.**	**15**	0.7	98.8	0.5	12.808370	124.364313	150	24.4	0.05	0.13	**0.18**
31A	**Montara Trans.**	**16**	8.9	87.8	3.3	12.823852	124.342990	165	27.3	0.05	0.18	**0.23**
33A	**Montara Trans.**	**17**	7.7	84.6	7.7	12.839865	124.320763	165	30.3	0.06	0.14	**0.20**
35A	**Montara Trans.**	**18**	16.1	82.6	1.3	12.855207	124.297077	168	33.3	0.08	0.31	**0.38**
37A	**Montara Trans.**	**19**	2.4	82.6	15.0	12.871035	124.274058	174	36.4	0.10	0.43	**0.53**
(E) Deeper (1-2 cm sediment depth) at the Cornea Seep and along the Montara transect												
18A	**Montara Trans.**	**9**	2.0	68.9	29.2	12.709353	124.497693	82	6.3	0.23	0.30	**0.53**
20A	**Montara Trans.**	**10**	2.9	78.0	19.1	12.725150	124.477790	86	9.0	0.04	0.14	**0.18**
22A	**Montara Trans.**	**11**	2.2	85.0	12.9	12.741950	124.453693	89	12.2	0.06	0.18	**0.24**
26A	Montara Transect	13	4.6	88.1	7.3	12.775197	124.409270	97	18.3	nd	nd	**nd**
30A	Montara Transect	15	0.7	98.8	0.5	12.808370	124.364313	150	24.4	nd	**nd**	**nd**
93B	Cornea Seep	57	15.3	61.4	23.3	13.655282	124.711738	90	110.3	nd	nd	**nd**
97B	Cornea Seep	58	14.8	56.8	28.5	13.652863	124.711642	89	110.0	nd	nd	**nd**
101B	Cornea Seep	59	0.4	56.1	43.5	13.510232	124.708268	109	94.5	nd	0.27	**0.27**
105B	Cornea Seep	60	5.5	49.9	44.6	13.412895	124.700795	106	83.7	nd	0.28	**0.28**

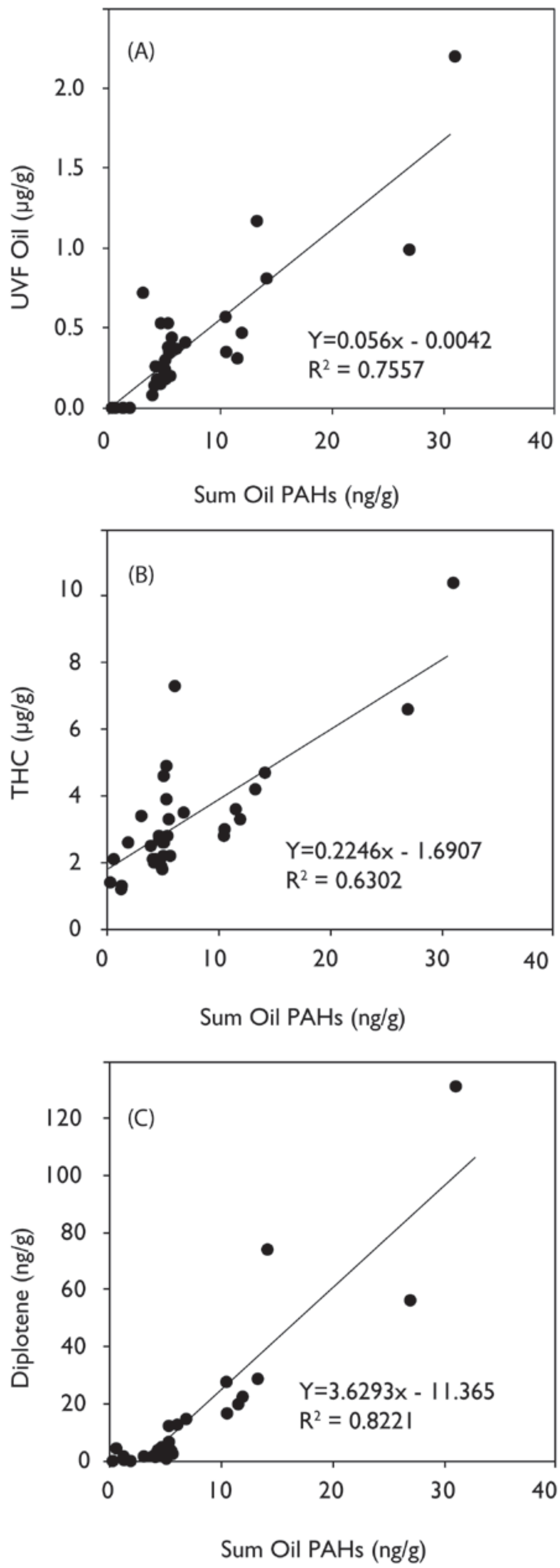

Figure 2.3 A-C. Highly significant correlations between (A) the UVF oil estimate and the GCMS SIM analysis of PAHs, (B) the GCMS scan method for total hydrocarbon analysis and the GCMS SIM analysis of PAHs, and (C) with the biomarker for oil degrading sulphate reducing bacteria (diploptene) and the GCMS SIM analysis of PAHS.

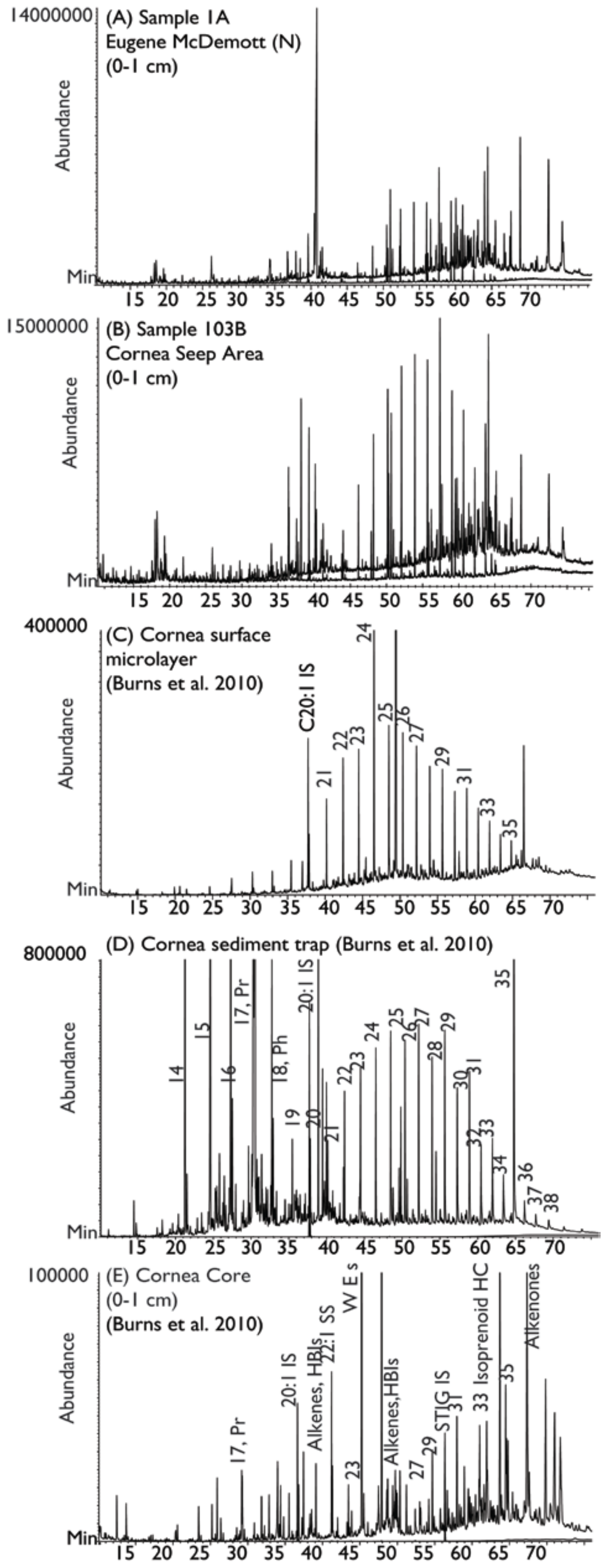

Figure 2.4 A, B, C, D, E. Reconstructed ion chromatograms of the hydrocarbons (and some biogenic lipids in sediments) from Eugene McDermott shoal, the Cornea Seep and from data collected in 2005 – see Burns et al. (2010) – where (C) is the top surface microlayer mousse sample, (D) is from a sediment trap at the Cornea Seep and (E) is surface sediment from core 3750 at the Cornea oil and gas seep site.

Table 2.3. Summary TOC and size fraction data and hydrocarbons based on GCMS analysis of samples selected from the UV/F analyses (See Table 2.2 and Figure 2.1 A and B). nd = non-detect, na = not analysed. Note all sediment samples were generally collected in duplicate and labelled A and B. UV/F Oil is the estimated concentration based on Ultraviolet Fluorescence analysis; THC is the total hydrocarbon concentration based on full scan GCMS; % UCM is the unresolved complex mixture under the peaks; n-alkanes include pristane and phytane, Triterpanes (Triterp.) are the sum of 14 hopane compounds common in petroleum; Steranes (Ster) are the sum of 8 marker compounds common in petroleum; Diploptene (Diplop.) and fluorenone (Fluor.) are degradation markers.

No.	Site Name	TOC %	Mud %	Sand %	Gr. %	Dry Wt (g)	UVF Oil (µg/g)	THC (µg/g)	UCM (%)	n-Alkanes (ng/g)	Oil PAHs (ng/g)	Com. PAHs (ng/g)	Triterp. (ng/g)	Ster. (ng/g)	Diplop. (ng/g)	Fluor. (pg/g)
(A) Surficial (0-1 cm sediment depth) samples around Shoal perimeter																
1A	E. McD. (N)	1.26	85.2	14.8	0.0	14	2.2	10.4	96.8	717.4	31.03	1.82	28.23	3.06	131.30	229.5
3A	E. McD. (E)	0.85	70.2	29.6	0.2	18	0.81	4.7	96	369.2	14.15	1.01	33.61	1.91	74.10	117.6
5A	E. McD. (S)	1.54	87.4	12.6	0.0	13	0.99	6.6	87.6	1925.4	26.95	1.30	6.26	1.87	56.30	189.7
7A	E. McD. (W)	0.44	28.1	62.4	9.6	22	0.57	2.8	98.4	96.8	10.47	0.52	5.31	0.47	27.70	209.2
47B	Vulcan (N)	0.42	4.3	87.4	8.3	23	0.41	3.5	96.1	104.7	6.87	0.22	4.37	1.24	14.70	nd
51A	Vulcan (S)	0.37	5.6	86.5	8.0	23	0.37	7.3	90.5	1716.2	6.07	0.30	4.12	1.18	12.70	nd
65A	Bar. East (E)	0.14	0.1	80.4	19.5	28	nd	1.2	91.3	251.4	1.26	0.04	0.23	0.15	1.60	nd
77A	Bar. West (N)	0.17	0.4	93.1	6.5	22	nd	1.3	98.6	nd.	1.30	0.07	0.07	0.06	0.30	nd
83A	Echuca (N)	na	77.2	22.3	0.5	18	0.35	3	95.9	326.2	10.53	0.50	1.50	0.68	16.70	185.2
85A	Echuca (W)	na	42.4	49.1	8.5	25	nd	1.4	99.6	nd	0.29	0.04	0.80	0.05	nd	nd
(B) Surficial (0-1 cm sediment depth) samples on tops (i.e. <55 m water depth) of three shoals																
87B	Vulcan	na	0.3	51.9	47.8	25	nd	2.6	98	53.2	1.89	nd	0.09	nd	nd	nd
89B	Vulcan	na	0.1	81.4	18.5	26	nd	2.1	97.3	30.8	0.60	nd	0.12	nd	4.40	nd
(C) Surficial (0-1 cm sediment depth) samples around Montara wellhead platform and Cornea seep																
9A	Montara (W)	0.33	24.7	73.6	1.7	29	0.72	3.4	99.2	3.4	3.07	0.07	1.75	0.30	1.60	33.6
11A	Montara (S)	0.22	10.6	80.1	9.3	23	0.35	2.8	96.8	2.8	5.41	0.12	0.34	0.39	2.70	38.7
13A	Montara (E)	0.24	14.2	80.1	5.8	24	0.26	2	98.7	2	4.20	0.15	0.19	0.30	2.70	25.2
15A	Montara (N)	0.31	26.9	71.1	2.0	21	0.3	4.6	97.4	4.6	5.07	0.24	0.43	1.40	3.70	40.5
95B	Cornea	0.54	28.5	56.8	14.8	22	0.47	3.3	97.5	100.6	11.93	0.48	3.71	0.48	22.50	147.6
99B	Cornea	0.6	43.5	56.1	0.4	19	0.31	3.6	88	985.4	11.53	0.50	2.33	0.42	19.90	nd
103	Cornea	0.56	44.6	49.9	5.5	19	1.17	4.2	96.6	192.9	13.28	0.58	6.96	0.61	28.80	nd
(D) Surficial (0-1 cm sediment depth) samples along the Montara transect																
17A	Montara	0.29	29.2	68.9	2.0	20	0.18	2.1	98.4	2.1	4.33	0.16	0.38	0.07	3.80	27.7
19A	Montara	0.26	19.1	78.0	2.9	22	0.24	2.2	98.5	2.2	5.04	0.21	0.39	0.07	4.00	37.9
21A	Montara	0.29	12.9	85.0	2.2	22	0.44	2.2	97.8	2.2	5.65	0.15	0.35	0.17	2.50	60.9
23A	Montara	0.19	10.1	87.4	2.5	22	0.08	2.5	98	2.5	3.91	0.10	0.11	0.22	1.70	22.4
25A	Montara	0.22	7.3	88.1	4.6	22	0.14	2.1	97.7	2.1	4.10	0.12	0.11	0.04	1.40	29.4
27A	Montara	0.27	14.3	71.1	14.5	23	0.15	2.8	99.1	2.8	4.64	0.17	0.20	0.08	2.40	24.2
29A	Montara	0.28	0.5	98.8	0.7	22	0.18	2.6	96.2	2.6	5.09	0.14	0.05	0.04	0.80	33.5
31A	Montara	0.3	3.3	87.8	8.9	24	0.23	2.6	95.5	2.6	4.99	0.16	0.16	0.09	3.10	37.5
33A	Montara	0.32	7.7	84.6	7.7	23	0.2	3.3	81.4	0.1	5.52	0.17	0.25	0.11	3.60	nd
35A	Montara	0.28	1.3	82.6	16.1	22	0.38	3.9	97.5	3.9	5.31	0.23	0.83	0.22	6.70	nd
37A	Montara	0.55	15.0	82.6	2.4	22	0.53	4.9	97.3	4.9	5.31	0.23	0.83	0.22	12.30	55.2
(E) Deeper (1-2 cm sediment depth) at the Cornea Seep and along the Montara transect																
18A	Montara	0.31	29.2	68.9	2.0	20	0.53	2.7	97.3	2.7	4.67	0.19	0.66	0.25	4.80	44.8
20A	Montara	0.28	19.1	78.0	2.9	20	0.18	1.8	98.8	1.8	4.95	0.19	0.36	0.07	3.80	43.2
22A	Montara	0.23	12.9	85.0	2.2	23	0.25	1.9	98	1.9	4.83	0.20	0.22	0.09	2.50	28.5

Table 2.4. A. Summary parent and alkylated PAHs for Montara 2 shoals and banks samples (pg/g) for surficial (0-1 cm sediment depth) samples around Shoal perimeters.

Site Name:	NAPL (µg/g)	E. McD. (N)	E. McD. (E)	E. McD. (S)	E. McD. (W)	Vulcan N	Vulcan S	Bar. East (E)	Bar. West (N)	Echuca (N)	Echuca (W)
Sample No.		1A	3A	5A	7A	47B	51A	65A	77A	83A	85A
naphthalene	20	2028	737	2317	nd	162	422	266	361	1027	nd
C1-naphthalenes	546	3227	1301	3399	639	350	751	261	321	1249	nd
C2-napthalenes	1872	4453	1756	3791	1192	542	870	145	133	1558	nd
C3-naphthalenes	1484	1410	721	1656	648	358	388	70	76	594	5
C4-naphthalenes	1050	1668	786	1606	822	185	210	109	134	674	17
biphenyl	182	1036	474	997	200	nd	183	nd	nd	413	nd
C1-biphenyls	464	396	296	436	142	46	78	nd	nd	138	nd
C2-biphenyls	610	475	257	433	153	40	56	30	33	156	1
acenaphthylene	nd	194	116	244	41	-	30	13	36	122	25
acenaphthene	nd	351	222	378	85	16	91	22	19	101	nd
fluorene	79	338	185	401	158	69	85	nd	nd	148	nd
C1-fluorenes	115	330	144	342	122	73	74	23	22	152	nd
C2-fluorenes	200	627	247	507	254	277	137	39	33	308	nd
DBT	57	134	70	165	60	46	36	26	14	76	nd
C1-DBTs	28	14	5	10	6	5	8	nd	nd	nd	nd
C2-DBTs	50	40	28	25	286	439	25	17	6	39	2
C3-DBTs	28	617	85	85	299	544	147	63	18	108	nd
phenanthrene	392	1599	881	1837	758	392	327	nd	nd	666	nd
anthracene		304	198	359	111	46	55	nd	nd	156	nd
C1phenanthrenes/anthracenes	406	1232	399	953	364	248	184	5	8	469	nd
C2phenanthrenes/anthracenes	434	1391	732	879	566	513	270	3	3	251	nd
C3phenanthrenes/anthracenes	227	807	187	159	270	346	180	31	11	121	26
C4phenanthrenes/anthracenes	69	438	126	67	105	150	76	19	3	41	5
fluoranthene	4	1348	698	1368	723	429	146	nd	nd	614	103
pyrene	4	1714	924	1689	1319	967	187	nd	nd	398	nd
C2-fluoranthenes/pyrenes	29	702	357	684	236	124	133	37	19	220	nd
C2-fluoranthenes/pyrenes	27	568	223	407	155	91	98	34	11	131	7
C3-fluoranthenes/pyrenes	14	155	54	100	42	30	27	9	8	33	11
benz(a)anthracene	6	216	200	177	74	29	90	nd	nd	59	nd
chrysene	6	326	174	268	133	55	56	nd	nd	126	27
C1benz(a)anthracenes/chrysenes	13	39	47	38	18	7	23	nd	1	45	5
C2benz(a)anthracenes/chrysenes	7	360	136	151	54	31	208	2	6	36	6
C3benz(a)anthracenes/chrysenes	2	96	49	54	32	12	107	3	5	15	3
C4benz(a)anthracenes/chrysenes	1	2136	1157	724	332	194	228	12	4	180	20
benzo(b)fluoranthene	2	408	214	304	123	52	69	nd	16	126	24
benzo(k)fluoranthene	<1	110	64	78	39	13	21	nd	4	44	9
benzo(e)pyrene	4	381	236	289	119	53	79	nd	18	111	nd
benzo(a)pyrene		266	133	205	62	28	39	14	11	64	nd
perylene		258	181	240	72	53	80	22	12	109	26
indeno(1,2,3-cd)pyrene		261	152	169	77	30	39	9	10	65	nd
dibenz(a,h)anthracene	<1	44	20	29	13	6	9	nd	3	11	3

Table 2.4 B. Summary parent and alkylated PAHs for Montara 2 shoals and banks samples (pg/g) for surficial samples around Montara well head platform, Cornea seep, top of Vulcan Shoal and deeper (1-2 cm) samples along the Montara transect.

Site Name:	Montara (W)	Montara (S)	Montara (E)	Montara (N)	Cornea	Cornea	Cornea	Vulcan	Vulcan	Montara	Montara	Montara
Sample No.	9A	11A	13A	15A	95B	99B	103B	87B	89B	18A	20A	22A
naphthalene	163	296	220	317	1336	1518	1355	nd	nd	264	285	289
C1-naphthalenes	230	462	435	508	1831	1909	1847	nd	nd	453	508	560
C2-napthalenes	227	440	518	553	1657	1625	1768	1043	235	524	568	653
C3-naphthalenes	46	142	220	174	742	657	914	113	82	141	259	257
C4-naphthalenes	107	380	406	351	462	291	389	226	40	306	373	331
biphenyl	nd	97	86	108	530	525	557	258	nd	101	98	82
C1-biphenyls	15	50	51	82	184	189	209	nd	nd	52	18	50
C2-biphenyls	66	120	119	135	161	162	185	63	26	106	133	75
acenaphthylene	nd	nd	nd	nd	85	109	104	23	26	nd	nd	nd
acenaphthene	9	19	26	33	198	204	220	nd	nd	31	28	25
fluorene	nd	39	40	48	147	146	170	nd	nd	43	52	69
C1-fluorenes	23	50	52	56	121	105	133	nd	nd	54	61	69
C2-fluorenes	65	106	89	106	228	181	228	14	4	132	108	115
DBT	nd	25	22	27	67	60	62	nd	41	22	26	25
C1-DBTs	nd	nd	nd	nd	5	nd	4	11	4	nd	nd	nd
C2-DBTs	115	187	49	74	57	64	71	nd	nd	63	60	87
C3-DBTs	138	187	44	54	35	nd	72	nd	7	44	52	81
phenanthrene	105	242	214	290	809	749	880	nd	nd	258	272	271
anthracene	9	25	29	37	111	132	155	nd	nd	33	36	31
C1phenanthrenes/anthracenes	102	217	168	220	486	303	527	10	nd	209	196	222
C2phenanthrenes/anthracenes	193	278	190	274	517	408	580	5	nd	268	224	242
C3phenanthrenes/anthracenes	159	213	109	155	166	93	255	69	42	172	103	215
C4phenanthrenes/anthracenes	49	86	41	70	91	61	93	24	9	96	37	67
fluoranthene	253	335	180	257	326	350	425	nd	nd	217	263	285
pyrene	845	1143	586	726	453	595	733	nd	nd	637	810	398
C2-fluoranthenes/pyrenes	29	57	72	88	291	269	327	6	nd	87	84	80
C2-fluoranthenes/pyrenes	16	35	49	49	169	151	173	16	18	49	49	44
C3-fluoranthenes/pyrenes	6	10	12	16	32	41	30	5	3	9	4	17
benz(a)anthracene	7	13	15	25	128	145	144	nd	nd	20	23	18
chrysene	15	24	22	42	103	94	113	nd	32	40	45	33
C1benz(a)anthracenes/chrysenes	2	2	3	6	18	14	15	nd	nd	5	7	4
C2benz(a)anthracenes/chrysenes	11	8	38	26	46	41	47	2	nd	23	22	25
C3benz(a)anthracenes/chrysenes	6	10	9	15	27	10	15	1	13	10	8	7
C4benz(a)anthracenes/chrysenes	50	84	65	111	270	235	410	4	3	170	116	88
benzo(b)fluoranthene	18	27	31	57	120	111	137	nd	nd	43	41	35
benzo(k)fluoranthene	5	9	10	15	27	27	28	nd	nd	12	11	9
benzo(e)pyrene	15	28	41	49	110	121	125	nd	nd	44	43	38
benzo(a)pyrene	7	16	20	34	65	94	101	nd	nd	26	24	20
perylene	13	25	22	35	44	93	75	nd	15	28	21	20
indeno(1,2,3-cd)pyrene	11	16	17	35	67	58	80	nd	nd	28	28	18
dibenz(a,h)anthracene	nd	3	6	5	9	9	10	nd	nd	6	11	28

Table 2.4 C. Summary parent and alkylated PAHs for Montara 2 shoals and banks samples (pg/g) for surficial samples along the Montara transect.

Site Name:	Montara	Montara	Montara	Montara	Montara	Montara	Montara	Montara	Montara	Montara	Montara
Sample No.	17A	19A	21A	23A	25A	27A	29A	31A	33A	35A	37A
naphthalene	231	285	176	273	163	244	281	186	211	336	478
C1-naphthalenes	449	523	434	463	416	457	568	398	453	498	666
C2-napthalenes	506	568	578	485	570	570	627	501	598	519	740
C3-naphthalenes	162	211	303	165	254	259	406	644	682	908	1059
C4-naphthalenes	303	375	541	202	281	366	456	313	339	312	407
biphenyl	86	108	nd	89	nd	nd	82	78	76	124	201
C1-biphenyls	72	55	44	26	27	41	43	42	45	65	94
C2-biphenyls	109	150	106	67	66	70	80	73	76	97	133
acenaphthylene	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	48
acenaphthene	28	31	18	21	18	19	22	19	23	45	75
fluorene	48	49	65	42	50	62	58	46	58	53	80
C1-fluorenes	54	69	88	52	72	71	71	69	77	65	90
C2-fluorenes	96	154	144	83	112	118	115	115	117	115	151
DBT	26	24	24	22	19	23	26	25	135	22	34
C1-DBTs	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
C2-DBTs	30	54	177	77	88	78	104	123	120	81	100
C3-DBTs	20	37	200	34	42	58	53	79	66	51	97
phenanthrene	257	281	261	257	235	248	295	312	317	288	466
anthracene	33	37	36	34	30	30	34	38	42	48	77
C1phenanthrenes/anthrac	187	214	232	177	204	223	227	233	245	258	402
C2phenanthrenes/anthrac	210	253	305	189	217	273	225	263	276	267	434
C3phenanthrenes/anthrac	96	160	288	106	103	180	109	128	146	145	288
C4phenanthrenes/anthrac	44	47	92	39	33	74	37	37	38	39	77
fluoranthene	231	238	305	320	364	322	382	396	416	151	312
pyrene	722	731	832	473	502	488	537	552	555	237	454
C2-fluoranthenes/pyrenes	72	85	97	67	84	79	81	80	88	121	194
C2-fluoranthenes/pyrenes	40	42	60	32	47	44	44	41	41	62	97
C3-fluoranthenes/pyrenes	5	4	23	3	5	15	4	5	4	16	16
benz(a)anthracene	18	22	25	15	14	16	15	18	23	28	52
chrysene	31	39	48	22	24	25	24	30	50	39	91
C1benz(a)anthracenes/chr	5	6	5	5	3	5	6	5	7	6	23
C2benz(a)anthracenes/chr	26	26	29	11	15	20	21	22	27	40	68
C3benz(a)anthracenes/chr	8	9	8	7	3	30	3	9	15	15	28
C4benz(a)anthracenes/chr	105	129	89	46	31	109	25	87	119	231	539
benzo(b)fluoranthene	36	45	33	22	26	38	29	37	42	50	100
benzo(k)fluoranthene	9	12	12	7	8	11	10	11	14	14	28
benzo(e)pyrene	37	49	40	28	33	41	41	40	47	56	110
benzo(a)pyrene	21	29	18	15	15	20	18	18	17	35	64
perylene	23	26	20	13	12	24	27	26	31	31	61
indeno(1,2,3-cd)pyrene	20	30	21	10	13	23	16	21	21	32	70
dibenz(a,h)anthracene	4	6	5	nd	3	5	5	3	5	5	11

Table 2.5 A. Summary triterpane and sterane biomarkers for Montara 2 shoals and banks surfical sediment samples (pg/g).

Location:	NAPL (µg/g)	E.McD. (N)	E.McD. (E)	E.McD. (S)	E.McD. (W)	Vulcan (N)	Vulcan (S)	Vulcan	Cornea	Cornea	Cornea
Sample ID:		1A	3A	5A	7A	47B	51A	87B	95B	99B	103B
diploptene		131346	74144	56317	27681	14683	12740	nd	22506	19938	28780
fluorenone		230	118	190	209	nd	nd	nd	148	nd	nd
Ts C27 22,29,30 trisnorneohopane	0.15	657	430	306	nd	183	236	44	nd	nd	276
Tm C27 22,29,30-trisnorhopane	0.14	nd	17301	nd	nd	301	165	39	219	nd	458
C29H-17a,21B-30-norhopane	0.34	1916	1294	994	333	170	232	6	266	288	379
C30H-17a(H)21B(H)-hopane	0.63	4870	2478	nd	1144	1388	1170	nd	679	nd	1657
C31HS	0.32	2710	1595	nd	582	656	602	nd	460	nd	740
C31HR	0.26	15034	9433	4410	2482	581	620	nd	1230	1465	2465
C32HS	0.23	738	nd	nd	272	326	292	nd	140	118	147
C32HR	0.2	2304	1082	555	493	298	347	nd	719	458	839
C33HS	0.09	nd	nd	nd	nd	311	309	nd	nd	nd	nd
C33HR	0.08	nd	nd	nd	nd	158	143	nd	nd	nd	nd
C34HS	0.08	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
C34HR	0.03	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
C35HS	0.02	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
C35HR	0.03	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
C27ba20S	0.11	nd	nd	nd	nd	57	76	nd	nd	nd	nd
C27ba20R	0.07	35	172	17	nd	44	nd	nd	nd	nd	nd
C27abb20R	0.07	nd	nd	351.4	nd	255	210	nd	nd	nd	nd
C27abb20S	0.03	nd	nd	nd	nd	134	776	nd	nd	nd	nd
C28abb20R	0.05	146	69	451	nd	115	nd	nd	nd	nd	nd
C28abb20S	0.03	2477	16454	1265	466	185	120	nd	481	420	610
C29abb20R	0.12	256	1113	121	nd	265	nd	nd	nd	nd	nd
C29abb20S	0.09	147	680	73	nd	185	nd	nd	nd	nd	nd

Table 2.5 B. Summary triterpane and sterane biomarkers for Montara 2 shoals and banks surfical sediment samples (pg/g).

Location:	Montara (W)	Montara (S)	Montara (E)	Montara (N)	Montara	Montara	Montara	Montara	Montara	Montara	Montara	Montara	Montara	Montara	Montara	Montara	Montara	Montara
Sample ID:	9A	11A	13A	15A	17A	18A	19A	20A	21A	22A	23A	25A	27A	29A	31A	33A	35A	37A
diploptene	1560	2746	2672	3680	3792	4775	4030	3762	2544	2469	1748	1378	2389	815	3079	3604	6688	12327
fluorenone	34	39	25	40	28	45	38	43	61	29	22	29	24	33	38	nd	nd	55
Ts C27 22,29,30 trisnorneohopane	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Tm C27 22,29,30-trisnorhopane	93	nd	nd	nd	nd	155	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
C29H-17a,21B-30-norhopane	nd	50	nd	72	73	nd	67	67	nd	nd	nd	23	50	nd	53	62	127	361
C30H-17a(H)21B(H)-hopane	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	933
C31HS	381	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
C31HR	478	287	191	361	303	505	327	293	347	219	108	85	149	50	111	183	401	1070
C32HS	215	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
C32HR	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	298	nd
C33HS	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
C33HR	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
C34HS	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
C34HR	348	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
C35HS	113	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
C35HR	125	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
C27ba20S	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
C27ba20R	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
C27abb20R	nd	168	194	588	nd	nd	nd	nd	nd	nd	175	nd	nd	nd	nd	nd	nd	nd
C27abb20S	139	81	27	703	18	23	29	41	34	22	13	16	12	10	22	13	37	25
C28abb20R	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
C28abb20S	nd	nd	nd	nd	nd	49	nd	nd	nd	nd	nd	nd	43	nd	36	52	71	297
C29abb20R	107	100	46	65	31	132	26	20	77	43	16	13	16	17	21	26	65	54
C29abb20S	57	40	34	47	23	43	17	14	55	29	13	10	12	13	15	17	47	35

Table 2.6 Hydrocarbons in surface sediment grabs and cores reported in Burns et al. 2010 compared with Banks and Shoals samples from 2011.

Station & Sample Number	Water Depth (m)	Depth (cm)	THC (µg/g)	∑ Oil PAHs (ng/g)	Distance from well (km)
Burns et al. (2010) Collected 2005					
Cornea Grab 3749	110	0-2	< 0.1	4.3	94.5
Cornea Core 3750	89	0-1	1.7	7.6	110.2
Cornea Grab 3748	107	0-1	0.2	3.9	82.53
Cornea Core 3751	108	0-1	1.2	1.2	94.5
Cornea Grab 3747	88	0-1	< 0.1	13.5	56.3
This Study					
103B Cornea Seep	106	0-1	4.1	0.6	83.7
1A Eugene McDermott Shoal (N)	146	0-1	10.4	31.0	41.4
5A Eugene McDermott Shoal (S)	155	0-1	6.6	27.0	47.6
15A Montara WHP	82	0-1	4.6	5.1	3.0
37A Montara Transect	174	0-1	4.9	5.3	36.4

2.3.4 Spatial patterns of hydrocarbon concentrations

A number of different sampling strategies were used to examine the pattern of hydrocarbon concentrations in the sediment potentially associated with the Montara uncontrolled release, including sampling around shoals of different distance from the platform and the flat, plateau areas of a number of shoals. Positive controls were also used which involved sampling areas where hydrocarbon contamination is expected, such as the natural hydrocarbon seeps around the Cornea oil and gas field. To further explore the spatial patterns, the relationship between the sediment hydrocarbon concentration and (a) distance from the platform and also (b) oil exposure based on the analysis of Study 7.1 of The Monitoring Plan for the Montara Well Release Timor Sea (Asia-Pacific ASA 2010a) was examined. This analysis used the estimate of hydrocarbon levels from the UV/F analysis, as opposed to the GCMS data, since there were more data points available and since there was a significant correlation between estimates of sediment hydrocarbon concentrations by the UV/F analysis and THC and or ∑Oil PAHs (via the GCMS, Figure 2.3A, B). For comparability, the relationship was restricted to only surficial samples (i.e. top 0-1cm), did not include samples collected from the shallower plateau areas or from the Cornea Seeps area, and only sediment samples that were classified as >50% mud and <50% gravel were used (see Figure 2.2).

The relationship between oil (µg/g) versus (a) distance and (b) maximum oil exposure were modelled using generalized additive mixed models (GAMMs) (Pinheiro and Bates 2000; Zuur et al. 2009). GAMMs extends the generalized additive model (GAM) to include random effects to account for correlation among observations on the same sampling unit (i.e. shoal). For each model, the fixed component (covariates that are not influenced by the hierarchical structure in the data) was either distance (Km) or maximum oil exposure. The fixed component or predictor variable were either linear or non-linear, therefore GAMMs were applied because these models can accommodate both types of variables. The random effects component of the model accounts for the spatial variation within and between shoals and explains the hierarchical structure of the data. Therefore observations within each shoal shared the same spatial variability and were regarded as not independent. The oil and distance variables were log transformed. The maximum oil exposure ranged from 0 to 7802 units (see Fig. 2.5B), therefore this variable was scaled by subtracting the observed values by the mean and dividing by the standard

deviation. Various measures of goodness of fit were applied to identify the 'best' model, these measures included adjusted R^2, Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC) and the (restricted) log-likelihood test. All models were analysed using the R (R Development Core Team 2007) function *gamm*.

Overall, considering the P and R^2 (adj) values, the data in Figure 2.5A and Table 2.7 shows that there was a significant correlation between UV/F sediment hydrocarbon concentrations and distance from the Montara WHP (Table 2.7).

Table 2.7: Summary of GAMMs results for two models. Where 'edf' is estimated degrees of freedom. Also provided is the adjusted (adj) R^2.

	edf	F	P	R^2 (adj)
Oil = Distance (Km)	1	28.710	<0.0001	0.339
Oil = Max.oil.exp	1.88	6.423	0.0044	-0.199

The analysis in Figure 2.5B shows that although the highest hydrocarbon concentration was found in a sample closest to the platform (sample 9A), there was no significant relationship between oil concentration and the modelled exposure index. Note that if the adj R^2 value is negative, as with the oil exposure relationship, then the mean of the data provides a better fit to the data than the GAMM.

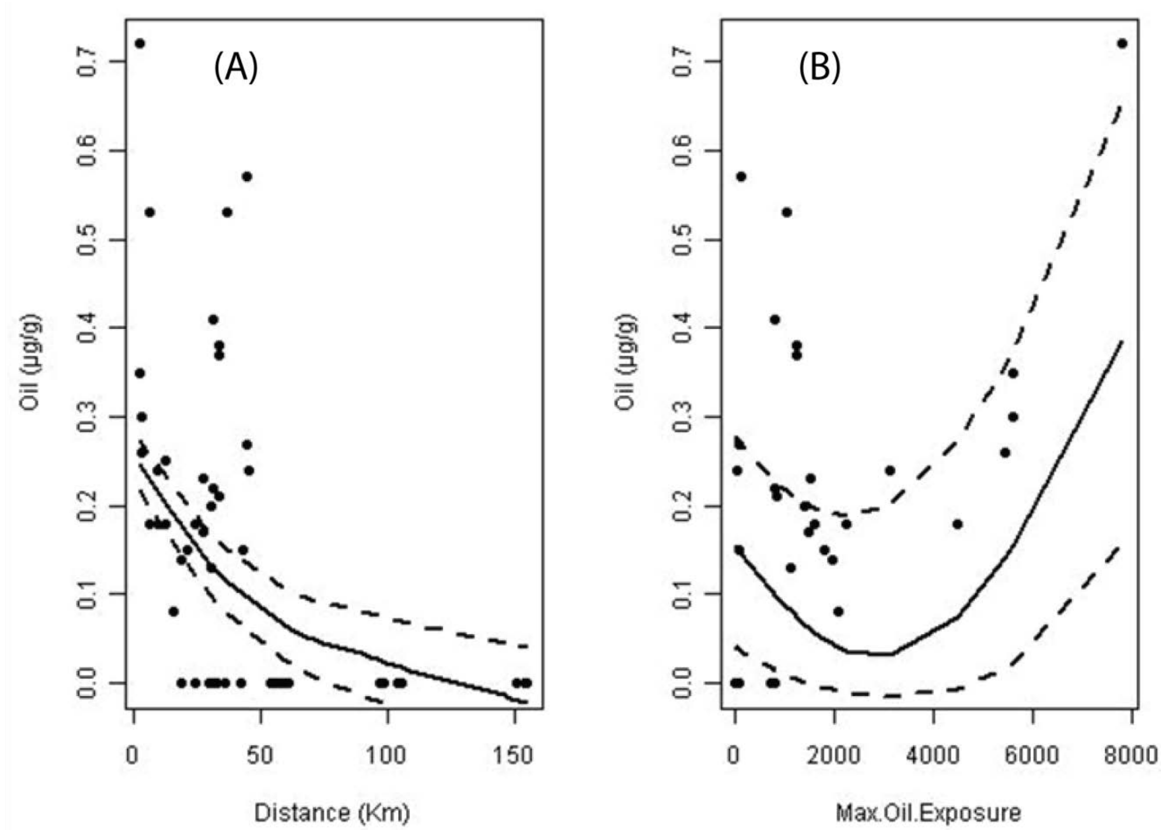

Figure 2.5: Plot of relationship between oil (µg/g) and (A) distance (Km) from the Montara WHP and (B) maximum oil exposure which is the cumulative particle count in 1.1 × 1.1 km pixels over the 92 day duration of the spill modelled in study S 7.1 (Brian King pers. comm. – see Asia-Pacific ASA 2010a) . The points are observed values, solid line is the predicted values and dashed line is the predicted 95% confidence interval.

In addition to the near-shoals sampling, Figure 2.6 show a more detailed analysis of the sediment hydrocarbon concentrations along the transect running from comparatively shallow water (80 m) 2.6 km SW of the Montara WHP past the shelf break and into comparatively deeper water (180 m) 37 km from the Montara WHP (see Fig 2.1A, Inset 1). Since the samples at each of these locations were analysed by GCMS, the relationship is examined as THC versus distance (km from the platform).

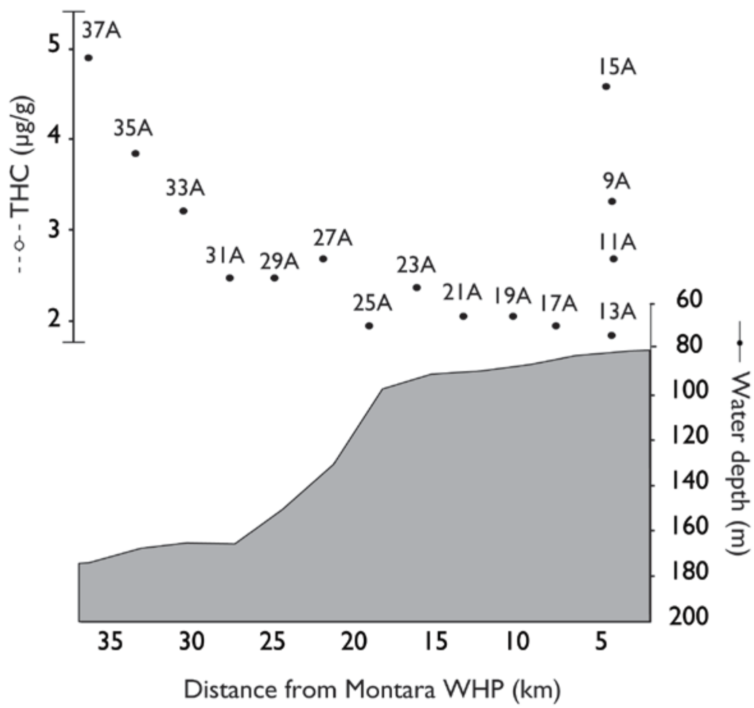

Figure 2.6: Plot of the relationship between THC **(µg/g) as measured by** GCMS analysis and distance (km) from the Montara WHP).

The data shows initially high concentrations around the Montara WHP but that once past the mid-shelf break, there is an increase with increasing distance from the platform (Figure 2.6). It is not clear why the hydrocarbon concentrations in deeper water are higher than in the shallow water >3 km from the platform. It is unlikely the pattern is related to dispersant application which was restricted to the shallower shelf water within <15 km of the WHP (Asia-Pacific ASA 2010b). It is possible that the pattern is related to the shelf break and meso-scale oceanography patterns and sedimentology, such that faster moving barotrophic tidal currents slow at the shelf-break, creating a down-slope deposition area where oil associated particles have been deposited. However, the sediment particle size analysis (Table 4.2) does not support this idea, as there is no evidence to indicate the sediments in deeper water contain finer sediment particles as would be expected in a depositional zone.

At the location of the Montara WHP, the depth of the surface mixed layer changes seasonally, but is generally between ~70 and 100 m deep. Water temperatures in the upper 100 m vary between 26-30°C, whilst at 200 m temperatures range from 15-20 °C (Brinkman et al. 2010). The observed pattern could therefore be related to faster breakdown/degradation of hydrocarbons in the shallower, ~10°C warmer waters of the shelf than cooler, deeper waters.

Since it was not possible to source match (see previously) it is not possible to unequivocally attribute the measured hydrocarbons along the transect depicted in Figure 2.6 to the Montara reservoir (even the comparatively high values immediately beside the platform). There is a background presence of

petroleum hydrocarbons in the Timor Sea which could originate from the oil industry, passing ships, discharge from fishing boats and from natural oil seeps (see Burns et al 2001, 2010).

2.3.5 Levels of hydrocarbons compared with Benchmarks

With the caveat that the 2010 and 2011 surveys were conducted many months after the uncontrolled release, and hence the worse-case scenario is unknown, it is instructive to compare the results of the surveys to Sediment Quality Guidelines or benchmarks. PAHs are widely accepted as toxic components of petroleum hydrocarbons and the US EPA (2003) has based guidelines on a tested equilibrium model. Similar guidelines for a subset of the PAHs were published by Simpson et al (2005) and by ANZECC/ARMCANZ. (2000).

Interim Sediment Quality Guidelines (I-SQGs) are available for PAHs in Australia and New Zealand (ANZECC/ARMCANZ 2000 and Simpson et al. 2005), based on guidelines developed in the US (Long et al. 1995; Donald et al. 1996; Buchman 2008). Table 2.8 has the values of a subset of the PAH data from this study normalized to the 1% organic carbon content for direct comparison with these guidelines (Simpson et al. 2005). The guidelines for the 'Trigger Values' requiring continued monitoring are shown for PAHs in the table as ISQG Low and the second column shows ISQG High which demand remediation in certain circumstances. All values for individual PAHs and for the sum (Σ) of low molecular and high molecular weight PAHs are well below the ISQG Low (Trigger) values.

Table 2.8. Parent and alkylated PAHs (ng/g DW normalized to 1% TOC) in the six sediment samples compared with sediment toxicity guidelines for Australia published by Simpson et al. (2005).

Sample number	1A	3A	5A	95 B	99B	103B	ISQG Low	ISQG High
naphthalene	1.61	0.87	1.50	-	0.27	0.75	160	2100
C1-naphthalenes	2.56	1.53	2.21	1.45	0.58	1.34		
acenaphthylene	0.15	0.14	0.16	0.09	-	0.05	44	640
acenaphthene	0.28	0.26	0.25	0.19	0.03	0.16	16	500
fluorene	0.27	0.22	0.26	0.36	0.12	0.15	19	540
phenanthrene	1.27	1.04	1.19	1.72	0.65	0.58	240	1500
anthracene	0.24	0.23	0.23	0.25	0.08	0.10	85	1100
∑ LMW PAHs σ	6.38	4.28	5.80	4.07	1.73	3.14	552	3160
fluoranthene	1.07	0.82	0.89	1.64	0.72	0.26	600	5100
pyrene	1.36	1.09	1.10	3.00	1.61	0.33	665	2600
benz(a)anthracene	0.17	0.24	0.11	0.17	0.05	0.16	261	1600
chrysene	0.26	0.20	0.17	0.30	0.09	0.10	384	2800
benzo(a)pyrene	0.21	0.16	0.13	0.14	0.05	0.07	430	1600
dibenz(a,h)anthracene	0.03	0.02	0.02	0.03	0.01	0.02	63	260
∑ HMW PAHs σ	3.11	2.53	2.43	5.28	2.52	0.94	1700	9600
∑ LMW and HMW PAHsσ	9.49	6.81	8.23	9.35	4.25	4.09	4000	45000

Table 2.9. Parent and alkylated PAHs (µg/g OC) in the five sediment samples compared with sediment toxicity guidelines published by EPA (2003). Concentration listed in Table 2.4 were normalized to the TOC content of the sediments listed in Table 2.3 and divided by the EPA threshold for toxicity. Summary values approaching 1 are considered toxic (see text).

Sample:	1A	3A	5A	95 B	99B	103B	EPA
	E McD. (N)	E McD. (E)	E McD. (S)	Cornea	Cornea	Cornea	$C_{oc,pah,vcv\ ug/goc}$
	$ESBTU_{FCV}$	$ESBTU_{FCV}$	$ESBTU_{FCV}$	$ESBTU_{FCV}$	$ESBTU_{FCV}$	$ESBTU_{FCV}$	
naphthalene	0.00042	0.00023	0.00039	0.00064	0.00066	0.00063	385
C1-naph	0.00058	0.00034	0.00050	0.00076	0.00072	0.00074	444
C2-naph	0.00069	0.00041	0.00048	0.00060	0.00053	0.00062	510
C3-naph	0.00019	0.00015	0.00019	0.00024	0.00019	0.00028	581
C4-naph	0.00020	0.00014	0.00016	0.00013	0.00007	0.00011	657
biphenyl	0.00021	0.00014	0.00017	0.00025	0.00023	0.00026	*385*
C1-biphen	0.00007	0.00008	0.00006	0.00008	0.00007	0.00008	*444*
C2-biphen	0.00007	0.00006	0.00006	0.00006	0.00005	0.00006	*510*
acenaphthylene	0.00003	0.00003	0.00004	0.00003	0.00004	0.00004	452
acenaphthene	0.00006	0.00005	0.00005	0.00007	0.00007	0.00008	491
fluorene	0.00005	0.00004	0.00005	0.00005	0.00005	0.00006	538
C1-fluor	0.00005	0.00003	0.00004	0.00004	0.00003	0.00004	581
C2-fluor	0.00007	0.00004	0.00005	0.00006	0.00004	0.00006	686
DBT	0.00002	0.00001	0.00002	0.00002	0.00002	0.00002	*594*
C1-DBT	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	*670*
C2-DBT	0.00000	0.00000	0.00000	0.00001	0.00001	0.00002	*746*
C3-DBT	0.00006	0.00001	0.00001	0.00001	0.00000	0.00002	*769*
phenanthrene	0.00021	0.00017	0.00020	0.00025	0.00021	0.00026	598
anthracene	0.00004	0.00004	0.00004	0.00003	0.00004	0.00005	594
C1-phen/an	0.00015	0.00007	0.00009	0.00013	0.00008	0.00014	670
C2-phen/an	0.00015	0.00012	0.00008	0.00013	0.00009	0.00014	746
C2-phen/an	0.00008	0.00003	0.00001	0.00004	0.00002	0.00006	769
C4-phen/an	0.00004	0.00002	0.00000	0.00002	0.00001	0.00002	913
fluoranth	0.00015	0.00012	0.00013	0.00009	0.00008	0.00011	707
pyrene	0.00020	0.00016	0.00016	0.00012	0.00014	0.00019	697
C2-fluo/pyrenes	0.00007	0.00005	0.00006	0.00007	0.00006	0.00008	770
C2-fluor/pyrenes	0.00005	0.00003	0.00003	0.00004	0.00003	0.00004	*860*
C3-fluor/pyrenes	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	*949*
benzanthracene	0.00002	0.00003	0.00001	0.00003	0.00003	0.00003	841
chrysene	0.00003	0.00002	0.00002	0.00002	0.00002	0.00002	844
C1-benzan/chrys	0.00000	0.00001	0.00000	0.00000	0.00000	0.00000	929
C2-benzan/chrys	0.00003	0.00002	0.00001	0.00001	0.00001	0.00001	1008
C3-benzan/chrys	0.00001	0.00001	0.00000	0.00000	0.00000	0.00000	1112
C4-benzan/chrys	0.00014	0.00011	0.00004	0.00004	0.00003	0.00006	1214
benzo(b)fluor	0.00003	0.00003	0.00002	0.00002	0.00002	0.00002	979
benzo(k)fluor	0.00001	0.00001	0.00001	0.00001	0.00000	0.00001	981
benzo(e)pyrene	0.00003	0.00003	0.00002	0.00002	0.00002	0.00002	967
benzo(a)pyrene	0.00002	0.00002	0.00001	0.00001	0.00002	0.00002	965
perylene	0.00002	0.00002	0.00002	0.00001	0.00002	0.00001	967
indenopyrene	0.00002	0.00002	0.00001	0.00001	0.00001	0.00001	1115
dibenzanthracene	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1123
benzoperylene	0.00003	0.00002	0.00001	0.00001	0.00001	0.00002	1095
∑All	0.00433	0.00291	0.00324	0.00420	0.00373	0.00444	
∑EPA34	0.00382	0.00256	0.00289	0.00372	0.00331	0.00394	

The EPA guidelines include many of the full suite of alkyl substituted aromatic hydrocarbons common in petroleum products. Table 2.9 (overleaf) has the values of PAHs in the five most contaminated shoals sediments converted to $\mu g/g_{oc}$ and converted to Equilibrium Partitioning Sediment Benchmark Toxicity Units based on the methods described in EPA (2003). The number of compounds in the guidelines is limited to 34. The sum listed in Table 2.9 shows the sum for the 34 and the sum of total with the toxicity concentrations for compounds missing from the EPA list interpolated from similar structures.

For freshwater or saltwater sediments, if ΣESBTUFCV <1.0 then no effects from PAHs are expected, and if the ΣESBTUFCV >1.0, then sensitive benthic organisms may be unacceptably affected. Clearly all sediments are well below the toxic threshold.

2.4 Conclusion

In summary, ~17 months after the flow of hydrocarbons from the H1 well of the Montara reservoir was halted, surveys were conducted of hydrocarbon concentrations in sediments around the base of nine banks and shoals in the Timor Sea, ranging from <3 to ~150 km away from the Montara WHP. Additional sampling was conducted on the flat, plateau areas of a number of shoals, around the Montara WHP, and at multiple sites along a transect line extending ~35 km from the platform in a SW direction. Sediments from a natural seep in the Cornea oil and gas field were also sampled for comparison purposes.

The surveys indicated widespread, low level concentrations of oil, and concentrations at some sites (for example around Eugene Mc Dermott shoal and the WHP) that were nearly double levels that were measured before the uncontrolled release, including sediment collected from the Cornea seeps. Overall there was a spatial relationship between hydrocarbon concentration and the Montara WHP with higher values closer to the platform,.

Where detected, oil residues were found to be severely degraded without more of the low molecular weight PAHs, and with GCMS scans showing high molecular weight alkanes visible over an unresolved complex mixture of hydrocarbons, typical of a degraded oil pattern.

Due to the degraded nature of the oil, it was not possible to match the oil found in the sediments to the Montara reservoir (i.e. to source match). Previous studies in the area (Burns et al 2001, 2010) have shown there is a background presence of petroleum hydrocarbons which could originate from the oil industry, passing ships, discharge from fishing boats and from natural oil seeps. Since source matching was not possible, the origin of the oil in the sediment remains undetermined.

Irrespective of the source of the hydrocarbons, the concentrations at the time of the survey were very low, and PAH levels were several orders of magnitude lower than levels at which biological effects have been documented. Given the time that had elapsed between the uncontrolled release and the commissioning of the study, and given the associated problems with source matching, it is unlikely that the true spatial extent of any possible sediment contamination from the uncontrolled release will ever be categorically known.

It is recommended that in the event of future uncontrolled releases of this type and magnitude, that sampling of hydrocarbons in sediments is initiated immediately after a well is under control.

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3. Benthic Habitat Characterisation

3.1 Introduction

The preliminary 2010 survey of two submerged shoals in the region of the Montara well head platform (MWHP), Vulcan and Barracouta, found that both supported diverse biological communities across their shallow plateau areas (Heyward et al. 2010). In areas down to 40 m, bare sand and rubble were ubiquitous components of the benthos, but interspersed with abundant primary producers, dominated by algae, corals and seagrass. More than 50% of the seabed on both shoals was covered with sessile life. To the degree measurable from image analysis, there was no evidence of major recent disturbance or mortality in the biota.

The analysis of video and still images indicated that these shoals supported highly diverse ecosystems. They provide a variety of carbonate substrates, along with fine scale topographic complexity and, at least in places, hosted communities typically seen on many coral reefs. Spatial variability was noted at all scales; within transect, within shoal and between shoals. On both shoals extensive rubble and rock fields were common and tended to support plants and smaller invertebrates. These rubble fields were interspersed with lesser areas of consolidated, low relief reef, patches of coarse sand and isolated larger coral outcrops. Both shoals supported reef building corals, seagrass and algae, particularly the calcareous green algae *Halimeda* spp. However, there were also significant differences between Barracouta and Vulcan in both the presence or absence of some important organisms and their relative abundance.

Barracouta Shoal supported abundant algae, especially *Halimeda*, and very little seagrass. A very extensive and likely monoclonal field of soft coral, preliminarily identified as *Nephthea* sp. covered a significant proportion of the western margin of the shoal. In contrast, Vulcan Shoal was particularly notable for an extensive and lush field of the seagrass *Thallasodendron ciliatum* that was not seen on Barracouta.

Despite these two shoals being similar in size and plateau depth, statistical comparisons of the major benthic groups showed the shoal communities to be highly distinct. The causes of this variation are not clear, but may relate to disparate disturbance histories and founder effects from organisms that are able to proliferate locally, utilising either restricted propagule dispersal and/or asexual propagation. Both Barracouta and Vulcan Shoals were revisited as part of the nine-shoal group included in the 2011 expedition. The additional seven shoals were poorly described, with only coarse chart bathymetry and very little available biological data. Only non-destructive sampling methods were used, relying on imaged-based tools to identify biota. Digital multibeam acoustics provided bathymetry and geomorphology data both incrementally to assist other sampling during field survey and subsequently as an integrated spatial dataset during laboratory analysis of the biological data.

3.2 Methods

Each shoal was surveyed using a combination of multibeam acoustic swath mapping for bathymetry and geomorphology, towed video and still camera transects for benthos and deployed baited video (BRUVS®) for fish communities. Swath mapping coverage was complete, while benthic and fish sampling was spaced to provide broad representative samples across each shoal (e.g. Figure 3.1).

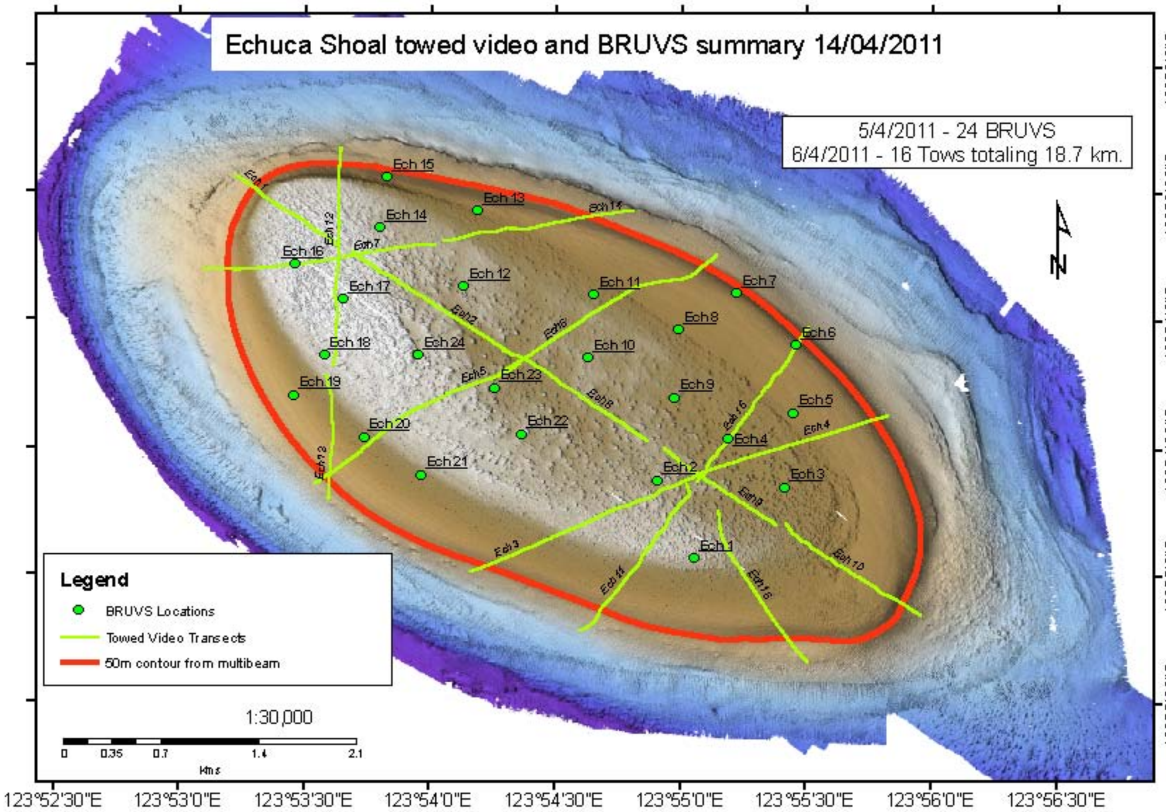

Figure 3.1. Echuca Shoal – typical field sampling effort showing multibeam coverage, tow video transect lines (pale green lines) and BRUVS deployments (green dots).

3.2.1 Physical characterisation

The nine survey shoals were located between 31-155 km from the Montara well head platform (Table 1.1). All had steep sides rising to plateau-like tops, with available chart bathymetry indicating average plateau depths in the 25-40 m range below sea level, but some areas on the shoal tops often 5-10 m shallower. With the exception of Vulcan and Barracouta Shoals, which were visited briefly in 2010 (Heyward et al. 2010), all shoals were poorly described, with limited available bathymetric data and no biological descriptions. The first step in characterising each shoal was to accurately map its location, determine the size and shape of the plateau boundary and develop an improved bathymetry using digital multibeam acoustic mapping across the entire shoal.

Multibeam swath mapping was undertaken using a Reson Seabat 7101. In the absence of accurate and detailed bathymetry from the available charts (AUS 314 Timor Sea, Sahul Banks navigation chart), the usual approach on arrival at a shoal chart location was to accurately locate the shoal feature using the multibeam, then undertake a series of perpendicular acoustic transects to establish the general shape of the shoal and its extreme boundaries. Swath mapping was then undertaken, generally at night, to progressively complete coverage of the shoal.

3.2.2 Setup of Multibeam Echo Sounder

The bathymetric and terrain surveys used a ship-born multibeam. The data was post-processed by Fugro Spatial (Perth) to a 2 m pixel size and supplied to AIMS. A Reson Seabat 7101 multibeam echo sounder was mounted through the moon pool shaft of the RV Solander on a retractable carriage. In order to

compensate for the angular offsets between the Reson Seabat 7101 transducer and the F180 IMU motion sensor and to check for navigation latency, a calibration was completed prior to the start of work. A final position and depth for each bathymetry data point was generated by the Reson Seabat 7101, which combined numerous data types including two way travel time, speed of sound, time and position, heading and attitude data. Real time quality control displays of bathymetry data (2D waterfall and coverage map) were monitored during acquisition to ensure that all peripheral devices were being logged and applied. The differential global positioning system (DGPS) provided reliable, stable and accurate positioning throughout the project. The navigation data was of good quality and processing of the data logged in Starfix.Seis was completed onshore using Fugro's processing software Starfix.Proc.

3.2.3 Collection of multibeam

Logged and processed position, heading, motion and speed of sound data were applied to raw multibeam data to produce a geo-referenced XYZ bathymetry dataset for each logging session. Gate and polar filters were applied to flag noise in the water column and to reject the outer beams of the multibeam swath. A 2D trace filter was subsequently applied to flag other erroneous data points. Each logging session of multibeam data was also edited manually to check for remaining data spikes and to re-accept soundings that may have been incorrectly flagged during filtering. Tide data was applied to processed bathymetry to reduce the dataset to Mean Sea Level. Adjacent swaths were compared to confirm that the draft, tide and speed of sound information had been applied correctly and a Valeport Midas sound velocity profile instrument was used to observe the speed of sound through the water column

The final bathymetry dataset (profiles shown in Figure 3.5) was binned at a size appropriate to the water depths at the top of each shoal and the multibeam system used. Data was gridded using a simple mean method and a 2 m cell size, with a 3-cell interpolation. The following is an overview of methods and data development for production of abiotic surrogates for use by the Montara shoals habitat mapping project.

3.2.4 Benthic habitat characterisation

The sessile biota and seabed substrate on the top of each shoal were surveyed down to maximum depths of approximately 60 m using towed video and still camera imagery as previously reported (Heyward et al. 2010). The 60 m depth contour typically occurred just below the upper shoal rims, often at depths around 40 m, as the substrate curved rapidly from the more horizontal shoal plateau regions in the 20-45 m depth range to the steeply sloping shoal sides. Discontinuing sampling as depths approached 60 m ensured that the shallower horizontal portion of each shoal plateau was adequately sampled, while avoiding inefficiencies and difficulties associated with sampling deeper, steeply sloping areas on the shoal sides. Previous AIMS research on the Timor Sea shoals indicated that habitats in less than 60 m were most likely to support diverse communities associated with benthic primary producer habitat. These shallower shoal regions were also closest to the sea surface where hydrocarbons were most likely.

The AIMS towvid system comprises a towed camera platform sending a live camera feed to a vessel-based image classification system (see Colquhoun et al. 2007, Fry et al. 2008; Heyward et al. 2010). The towed platform supports a forward facing video camera with lights, together with a downward-facing high resolution still camera and strobe system programmed to take sequential still images at fixed time intervals (Figure 3.2). The towed platform was deployed over the stern of the vessel, maintained within a meter of the seabed and towed at 1-2 knots (1.5 nominal) until a minimum distance of about 1.5 km, and up to 2.1 km was covered in a continuous line transect. On the vessel, a computer-based towvid program manages collation of position, depth, and operator-derived habitat classification data, which is captured in real time as an operator interprets the live video feed and then archived for subsequent

spatial analysis (Figure 3.3). At the completion of a transect the tow platform was retrieved to the vessel deck, still camera images downloaded and the camera systems serviced as required while the vessel steamed to the next transect station. Priority was given to surveying the shallow plateau regions of each shoal, identified by monitoring the live soundings, which tended to drop away quickly beyond 30-40 m depths. The location of each transect was nominal but designed to provide coverage across and along each shoal plateau region, relying on the multibeam data acquired as survey of each shoal progressed.

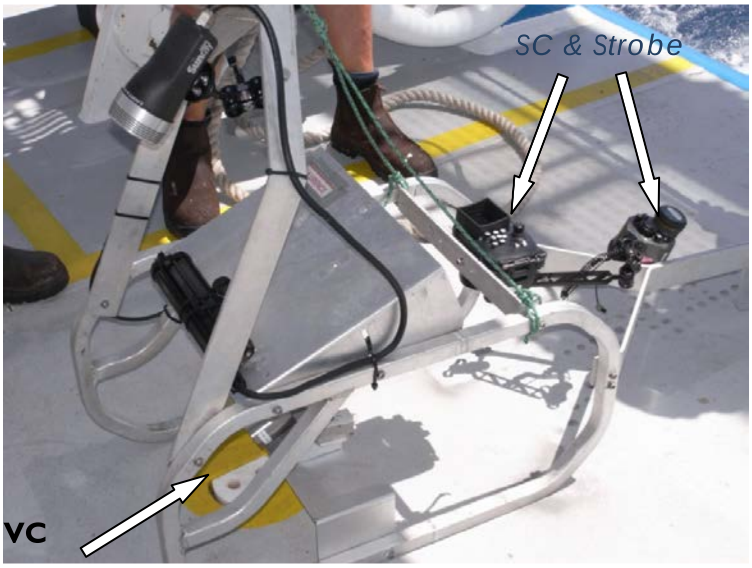

Figure 3.2. Towed body used for all transect surveys. A forward facing video camera (VC) provides live images to the ship, allowing the towed body to be “flown” just above the seabed while marine scientists classify the habitats. Positioned at the rear of the towed body a high resolution still camera (SC) with strobe takes downward facing, detailed images of the seabed every 5 seconds, for use in later analyses.

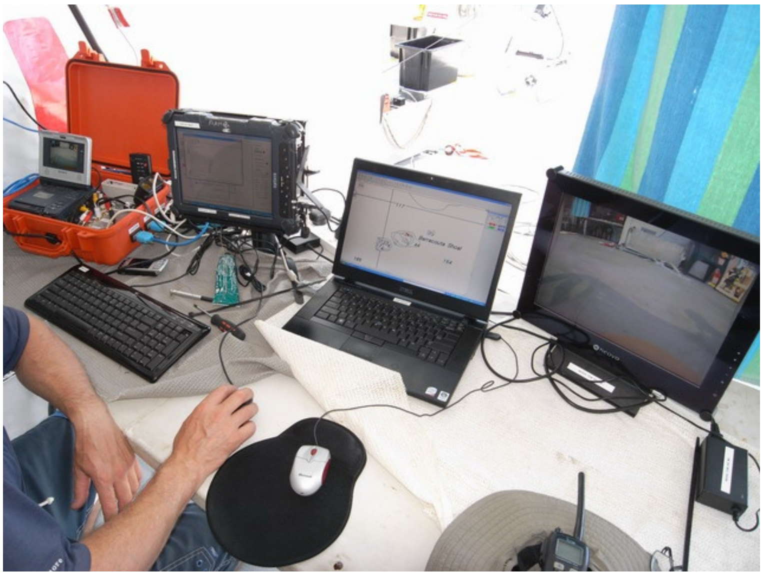

Figure 3.3. The AIMS towvid system in use on board the research vessel RV Solander during the survey. Live video is classified directly into a computer, with the observer keying in the appropriate classification from a variety of pre-programmed major habitat types, along with the associated data on position and depth. The video and this associated data are also recorded to tape and archived.

3.2.5 Still photo analysis

The still photo images for all transects were geo-referenced, based on corrected tow platform position data and time code synchrony, prior to being sub sampled at a standardized spatial separation then grouped for detailed point-intercept analysis. Based on previous experience of benthic habitats in this bioregion (Heyward et al. 1997, Heyward and Rees 1999; Heyward et al. 2010), a sampling interval between sequential images of 10 m along each transect was sought. Actual image spacing achieved varied from 6-10 m. The number of images collected and used in the analysis was proportional to the size of the shoal and total length of towvid transect conducted. After sorting and discarding poor quality photos, a sample totalling 16,000 images taken from all shoals was selected for detailed analysis in the current survey.

The downward looking still images of the seabed were analysed using a point intercept approach with the AIMS Reefmon software (Jonker et al. 2008). Reefmon is a benthic classification system developed by AIMS for the Long term monitoring (LTM) on the Great Barrier Reef. A preliminary multivariate pattern analysis with 2010 data from Vulcan and Barracouta Shoals using 20 verses 15, 10 and 5 points per image produced very similar major patterns (see Appendix 3.1). Consequently all images were analysed using the Reefmon database system, with five overlaid points classified per photo. The benthos under each superimposed point was identified to the highest possible taxonomic classification and/or morphotype. Categories of benthos include: hard corals, soft corals, algae, sponges, abiotic, indeterminate and other. Corals were potentially identified to species but more typically to genus or genus morphotype, e.g. *Acropora* tabulate. Reefmon can be modified to add classification categories appropriate to the region or habitat if necessary. For the purposes of the Montara shoals survey, sponge morphotypes categories were expanded to include the common sponge morphologies encountered in deeper water tropical shoals i.e. hollow massive, simple massive, erect branching, simple erect, erect laminar and clathrate. When seagrass was encountered during Reefmon classification, the rule applied was that a point was considered seagrass if it fell on seagrass leaf, rhizome or stalk. Crustose coralline algae (CCA) was regularly encountered during the classification process, and classified as such when found on rocks or consolidated pavement or reef-type substrate. CCA on free rubble and small stones, with the typical nodule appearance, was classified as Rhodoliths. In each image the relative abundance of key biota, such as corals, algae or seagrass were quantified using the Reefmon point-intercept software, which logged all data against transect, depth and position.

3.2.6 Data management

All data was collated in digital format and archived on the AIMS server. Multibeam data were collected as raw files and processing to ASCII XYZ grids for use with GIS and spatial analysis. The resulting derived files were added to the Montara archive.

Position and depth data derived from the ship's navigation package were associated with all field sampling. Towvid position, depth and habitat classification data were transferred in Microsoft Access database structure. Associated video files, were recorded to analogue mini DV tapes and archived also in avi format. Still photos associated with each towvid transect were recorded in jpeg format and georeferenced. Metadata for all sampling is included in **Appendix 1**.

3.2.7 Statistical analysis

Benthic composition within and between shoals

Benthic community structure was described as mean percent cover of major benthic groups at transect and shoal level, using the point intercept data derived from the high resolution still photos.

Comparison of similarities in the abundance of major biological groups between shoals was undertaken, using a cluster analysis of the towvid data. This identified which habitats dominated each shoal and how

shoals were grouped based on habitat. This is a fairly conservative method but highlights major habitat groups on each shoal. Data was excluded for groups that on average had less than 2.5% cover per shoal. The cluster analysis (complete linkage) was based on Hellinger transformed distance matrix (see Legendre and Gallagher 2001) of the major benthic groups, which is an ecologically meaningful transformation appropriate for community composition data.

Preparation of secondary datasets from multibeam.

A variety of secondary (textural) datasets which may correlate with seafloor properties were developed from the bathymetry using terrain analysis techniques. These techniques are applied to elevation data, quantifying the relationships among elevation values in small neighbourhoods to reveal textural differences. Using a gridded elevation (or bathymetry) dataset, calculations are run on a small number of cells surrounding each pixel. A 3 pixel radius analysis for illustration (Figure 3.4).

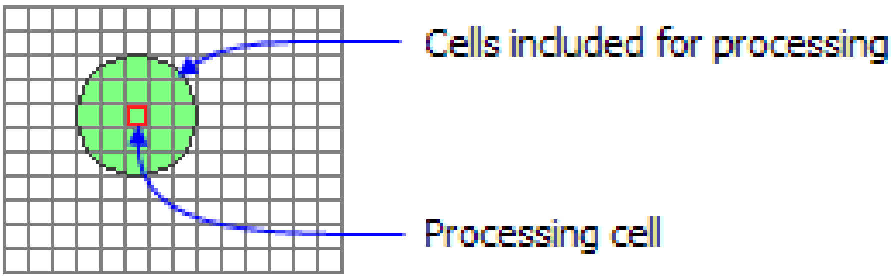

Figure 3.4: Example of defining local and neighbourhood cells for textural analysis. The red cell is the target cell and its neighbours for analysis are highlighted in green.

In this case, all neighbourhood calculations (such as the mean, mode or slope) are run on the central cell plus the 8 surrounding cells, and the value assigned to the central cell in the output, thus creating a derivative dataset. The full suite of datasets used for modelling the Montara shoals are described in Table 3.1. Textural variables were tested for autocorrelation and where two sets of variables were derived using a different measure and were highly autocorrelated (i.e. r^2 greater than 0.6) one of variables sets was excluded. This was repeated in a stepwise fashion so that the final dataset contained variables without significant autocorrelation.

Table 3.1. Datasets derived from multibeam bathymetry that were used as environmental surrogates variables for modelling biota, substrate and fish abundance/richness.

Predictor datasets	Definition	Source or Algorithm
Bathymetry (Depth)	Elevation relative to the Australian Height Datum (AHD), binned to 2 m.	Reson 7101 Multibeam, Fugro Geomatics
Depth	Bathymetry derived from Multibeam	ArcGIS Arc/Info 9.3
Standard Deviation*	Standard deviation of elevation (local neighbourhood analysis)	ArcGIS Arc/Info 9.3
Slope	First derivative of elevation: Average change in elevation/distance	ArcGIS Arc/Info 9.3
Aspect	Azimuthal direction of steepest slope	ArcGIS Arc/Info 9.3
Profile Curvature	Second derivative of elevation: Concavity/convexity parallel to the slope	ArcGIS Arc/Info 9.3
Plan Curvature	Second derivative of elevation: Concavity/convexity perpendicular to the slope	ArcGIS Arc/Info 9.3
Curvature	Combined index of profile and plan curvature	ArcGIS Arc/Info 9.3
Hypsometric index*	Indicator of whether a cell is a high or low point within the local neighbour	ArcGIS Arc/Info 9.3
Moran's I* r = 5	A weighted correlation coefficient used to detect spatial dependence. Calculated from the bathymetry.	Laffan, 1998
Local relief (Range)*	Maximum minus the minimum elevation in a local neighbourhood	ArcGIS Arc/Info 9.3
Rugosity (surface area)	Surface area of the local neighbourhood, and the ratio of the actual surface area to pixel area	Jenness, 2010

* Local neighbourhood analysis; run on circular kernels of radius 5,10,+25 and 50 pixels (pixels are 2 m)

3.2.8 Spatial Modelling

To infer spatial distributions of a) marine biota; b) abiotic substrate and c) fish abundance and species richness, we characterised environmental relationships in detail using the combination of towed video footage, digital stills, BRUVS fish counts, multibeam hydroacoustic data combined with a statistical modelling approach. Towed video and BRUVs observations provide the basic information quantifying what was found on the benthos, while bathymetry and textural datasets provide information on environmental characteristics, and give full coverage of the field area.

To model these relationships, we trialled three contemporary methods using a subset of models. These methods were random Forest, Boosted Regression Trees (BRTs) and a derived method Aggregated Boosted Trees (ABTs) and are all well suited to dealing with complex ecological datasets that contain correlated predictor variables and display non-linear relationships. While all methods performed well and while randomForest was considerably less time consuming to run, BRTs and ABTs consistently provided more accurate models. All final models used ABTs (De'ath 2007) because it: a) provides

estimates of standard errors with fits; b) has been documented to perform well with smaller datasets (for example BRUVs); c) is consistent with other methods used in modelling BRUVs data.

A detailed description of the application of this method with ecological data is outlined in De'ath 2007. The final construction was based on the results of a maximum of 5000 trees, three levels of interaction and five-fold cross validation (which was used to determine the optimal model size and to prevent over-fitting). This ensured that the model was representative of the area as a whole, and was not biased toward any particular subset of data. Plots of model responses with standard error are shown in Appendix 3C C3.1 to C3.14. Model accuracy statistics are shown in Table 3.1 and 3.2. R library and the library "abt" were used for tree construction of models and graphics (De'ath 2007).

In the case of towed video and digital still benthic analysis, the ABTs were evaluated using a subset of the still imagery observations reserved prior to modelling (~20% of the full dataset selected via variogram so as to largely spatially independent from the training data). The model accuracy was assessed by predicting the values against this blind validation dataset using receiver-operator characteristics (ROC) analysis. ROC are visualised as plots of model sensitivity (classification accuracy) versus specificity (false positive rate). The larger the area under the curve (AUC), the more robust the model for prediction (see Table 3.2). Models with AUC greater than 0.8 have high predictive power, values between 0.7 and 0.8 are acceptable and models with AUC of 0.5 or less have no power of discrimination (Hosmer and Lemeshow 2000). For the fish abundance and biomass analysis abt model performance was assessed by residual deviance and cross-validated correlation (Table 3.4)

The probability maps (values ranging between 0.0 to 1.0) were simplified to binary presence/absence maps (values equal to 0 or 1) for mapping. The threshold used to produce the binary maps was determined statistically using ROC. The probability value (see probability cutoff in Table 3.1) used as a threshold was determined to avoid extreme over or under-prediction (Sensitivity = Specificity). "Sensitivity = Specificity" finds the threshold where positive observations are just as likely to be wrong as negative observations. It is a good balance between false presence, false absence, and model accuracy particularly when the numbers of true presence values in a dataset are small. Sensitivity = Specificity is correlated to prevalence, so is very useful for modelling abundance of sparse biota which are given much lower thresholds than widespread species. However it is important to note that, rare species may give the appearance of inflated distribution, if maps are made with thresholds that have been optimized by this method (Manel et al. 2001).

3.2.9 Spatial mapping

For each shoal maps of composite spatial models and individual spatial models were produced. The composite spatial models were habitat maps of dominant classes of a) living biota and b) abiotic substrate (Figures 3.20 to 3.38). These included two habitat cover types; dominant (for high cover > 30% by area) and sparse (low cover < 30 % cover by area) For both substrate and biota the most spatially abundant five to seven habitats types were mapped. All remaining habitat types were amalgamated into "mixed dominate" or "mixed sparse".

Individual models were produced for particularly biodiverse and sensitive groups. These included the probability of occurrence for: a) live coral cover b) *Halimeda* cover (values between 0-1, 1 been high probability of presence, (Figures 3.39 – 3.47) c) BRUVs based fish total abundance (values are total n, d) BRUVs based fish total biodiversity (values are number of species) (refer to Chapter 4 for outputs).

3.2.10 Gradient analysis of benthos in relation to variables for oil spill

Photo level point intercept data, collected along each tow transect and analysed as described above, were obtained for each transect from each shoal. Data from below 50 m depth were discarded so that

the depth range of the data from all shoals was equivalent. Analysing the data at the photo level using presence/absence of categories in a logistic model proved to be too computationally intensive. However, because the transects were very large (covering 1.42 km on average) they were divided into sub-transects based on depth (ensuring a depth stratified design). To accomplish this, photos from each transect were binned into 10 m depth categories, and all photos along a transect continually occurring within that depth band were assigned to a single sub-transect. Sub-transects with less than five photos were discarded. This created a total of 411 sub-transects, for which the % cover of a range of benthic variables were calculated. Variables occurring frequently enough for analysis included three coarse scale benthic categories: total algal cover, total hard coral cover and total cover of sponges. At a finer taxonomic scale we also examined the total cover of Acroporidae and Pocilloporidae (Scleractinia), coralline algae and Ascidian (represented overwhelmingly by the small photosynthetic Ascidian *Lissoclinum sp*., see Heyward et al. 2010). In addition we used a principle components analysis (PCA), performed using the rda function in R to summarize the community structure of hard corals at the family level. The first PCA axis was used for this purpose, and explained 26% of the variability. All these response variables were examined graphically for normality and homogeneity of variance and in some instances a log10 or square-root transformation was performed to better meet the assumptions of this analysis.

To explore the effect of the uncontrolled release on the benthos, we used generalized mixed effect additive models (GAMMs) fitted via "gamm" from the mgcv library in R. This modeling approach allows the incorporation of random effects, which was necessary given the non-independence of our data. GAMMs also allow for non-linear relationships between the dependent and the predictor variables. For all model fits the number of knots was restricted (k=4) to avoid excessive over fitting by the models. Adjusting this up or down did not markedly change the R^2 obtained, nor the general patterns found.

Initially, we tested the necessity for a random effect of shoal. This was done by fitting a full (beyond optimal) model using several potentially important physical predictors (depth, aspect, lat, lon, slope and rugosity) and comparing Akaike Information Critetion AIC, (Burnham and Anderson 2002) values with and without the random effect (random = list (SHOAL=~1)). These models were fit using maximum likelihood with method = "REML", as recommended by (Zuur et al. 2009). Variogram's were used to examine the residual autocorrelation of the fitted models and were found to be adequate.

Once the appropriate random structure was determined, a full-subsets approach was used to determine the best "null" model, based on the most relevant available physical variables: We included a total of six potentially relevant physical predictors: depth (the median depth of the transect), aspect (rescaled as a vector between 0 and 180, where 0 is due North East and 180 is due South West), slope, rugosity variables, latitude and longitude (both rescaled to between 0 and 1 across the spatial scale of the study area). All possible models of 1 and up to 3 of the physical predictors were fitted using maximum likelihood (method = "ML") and compared using AIC. More complex models (4 variables +) were not fitted because preliminary analysis suggested none were preferred via AIC and because the total number of possible models becomes excessively large.

All models within 2 AIC of the best model were selected (as these are considered equally valid models, (Burnham and Anderson 2002) and subsequently used as "null" models for comparison to three oil spill variables: distance from the uncontrolled release, the minimum hours of our exposure (see Figure 1.4) and presence/absence of oil (derived from the sediment analysis data - see Chapter 2). Each oil spill variable was added to each of the null models and AIC and AIC weights (AICw, calculated following (Burnham and Anderson 2002)) used to compare this complete set of models. Log-likelihood ratio tests were used to determine if the best model with and without the oil exposure variables were significantly different.

3.4 Results

3.4.1 Broad scale characterization of habitat types

The central locations, mean depths (plateau), shoal profiles and sampling effort undertaken for each shoal are provided in Tables 3.2, 3.3 and Figure 3.5. Shoal morphology and the spatial distribution of the seabed survey transects across all shoals is shown in Figure 3.6. The abundance (% cover) of the dominant benthic groups for each transect and at reef level are plotted in Figures 3.7-3.15, with associated data provided in Appendix 3C.

Table 3.2. Shoal locations, towed video transect depth ranges, distance from uncontrolled release and relative exposure category.

Shoal	mean Lat	mean Long	mean depth (m)	min depth (m)	max depth (m)	dist from spill (km)	bearing	impact cat (Sea Surface Exposure)
Barracouta East	-12.5456	124.0336	26.8	17.9	44.4	56.56	284.47	Low
Barracouta West	-12.5612	124.0067	33.5	18.0	47.0	59.07	281.98	Low
Echuca I	-13.9028	123.9071	26.1	16.8	40.4	153.21	206.37	Low
Eugene McDermott	-13.0754	124.5828	37.5	19.2	60.8	44.99	174.40	Medium
Goeree	-12.8829	124.3427	35.5	22.8	46.4	31.65	222.33	High
Heywood	-13.453	124.0474	33.3	19.0	49.8	101.78	211.62	Low
Shoal 25	-12.5152	124.1733	36.1	31.5	44.3	43.43	293.72	Medium
Vulcan I	-12.8029	124.2816	29.7	16.3	46.2	31.42	242.42	High
Wave Governor Bank	-12.5702	123.5983	44.6	36.5	49.7	102.79	276.26	Low

Table 3.3. Shoal plateau areas, number of towvid transects and total transect lengths.

Shoal	**Size (50 m Contour) (km²)**	**Shape**	**No. Transects**	**Total Length of Transects (km)**
Barracouta East	5.76	Egg	18	26.5
Barracouta West	2.86	Circular	9	11.4
Echuca	11.52	Oval	16	29.9
Eugene McDermott	5.64	Oval	13	15.5
Goeree	2.95	Egg Elongated	14	16.1
Heywood	31.96	Oval	20	38
Shoal 25	1.96	Oval	13	13.8
Vulcan	12.54	Elongated Oval	24	33.1
Wave Governor Bank	0.82	Elongated Oval	7	6.1

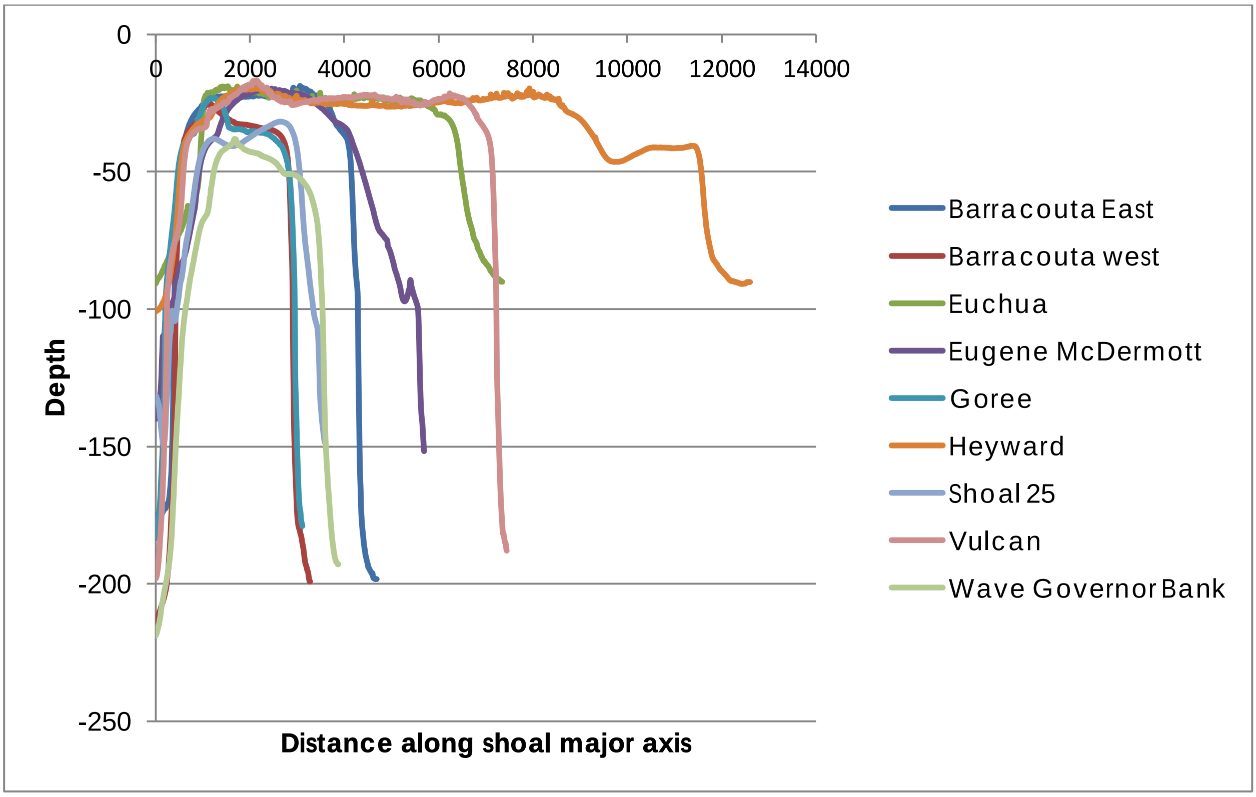

Figure 3.5. Cross section shoal depth profiles derived from a multibeam transect across the long axis of each shoal. Detailed plan views of each shoal morphology are shown in Figures 3.6-3.15.

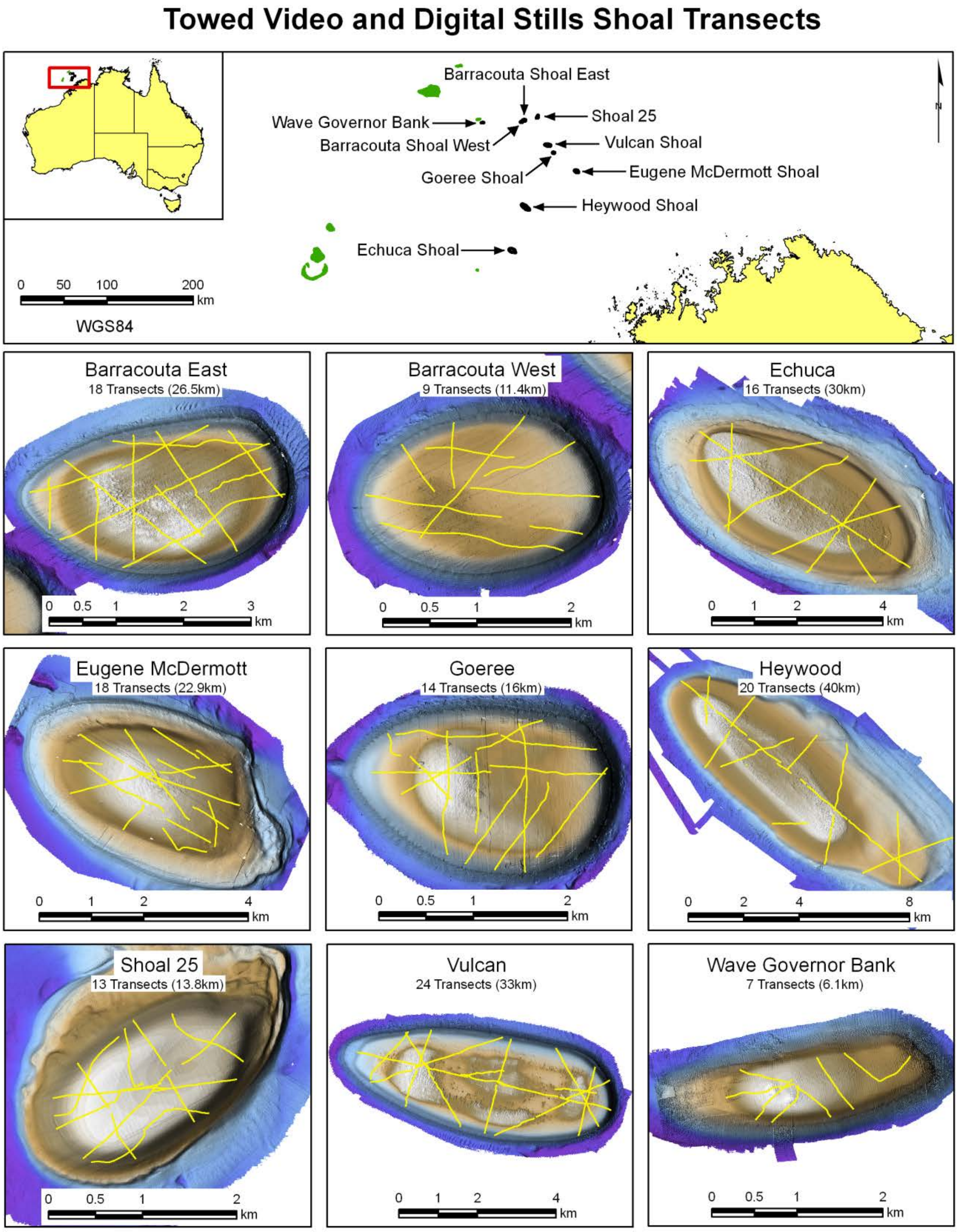

Figure 3.6. Multibeam swath coverage and location of completed benthic towed video transects on all shoals. The number and total length of survey transects completed on each shoal are shown. Shading for depth is colour coded for relative depths, consistent within each shoal only, for illustrative purposes.

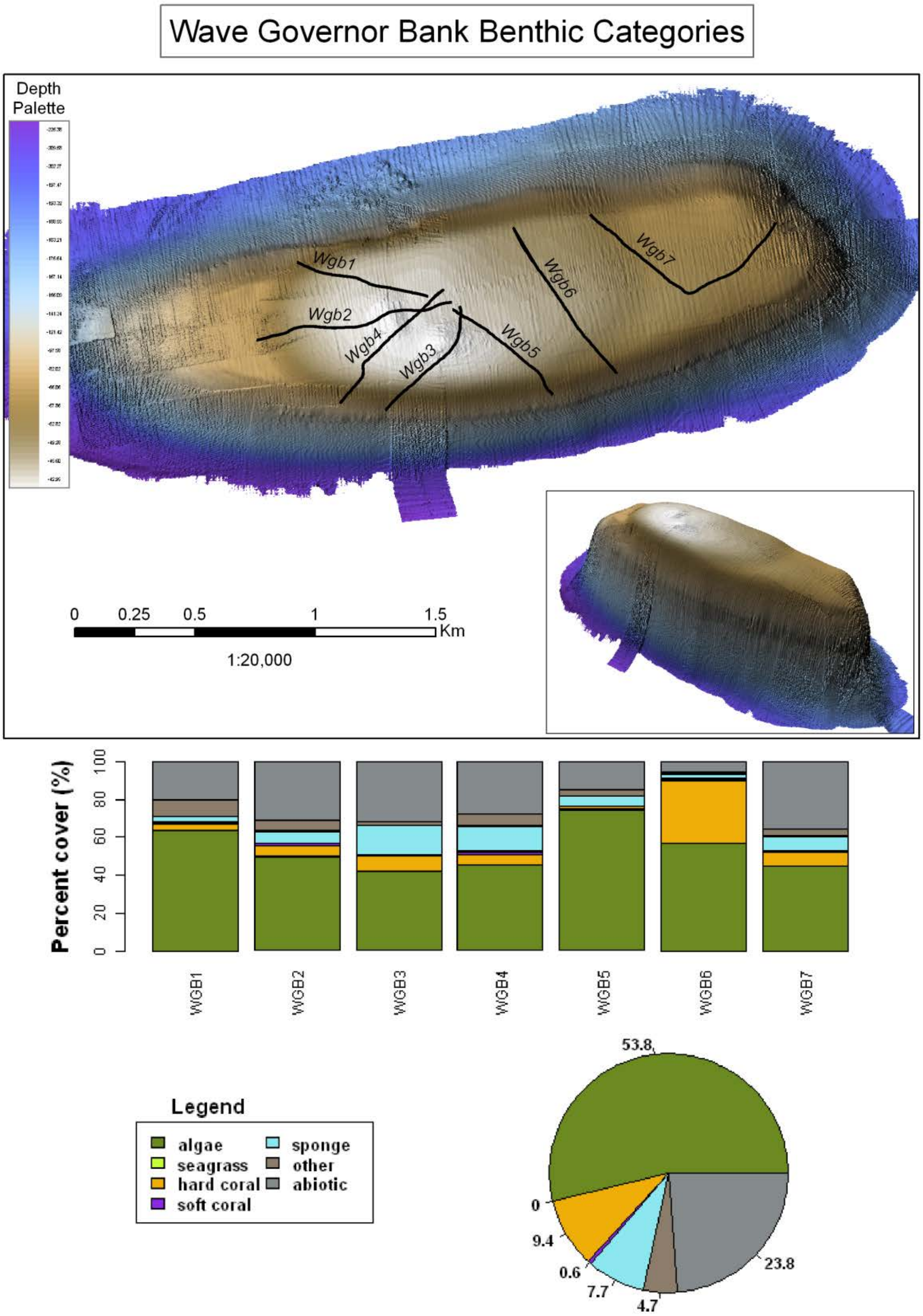

Figure 3.7. Wave Govenor Bank shoal morphology, depth and the abundance (% cover) of major benthic groups derived from image analysis of high resolution still photos taken using the AIMS towvideo system along the sampling transects indicated by the seven black lines in the upper map. Data for individual transects is shown in the histogram and means for the shoal in the pie diagram.

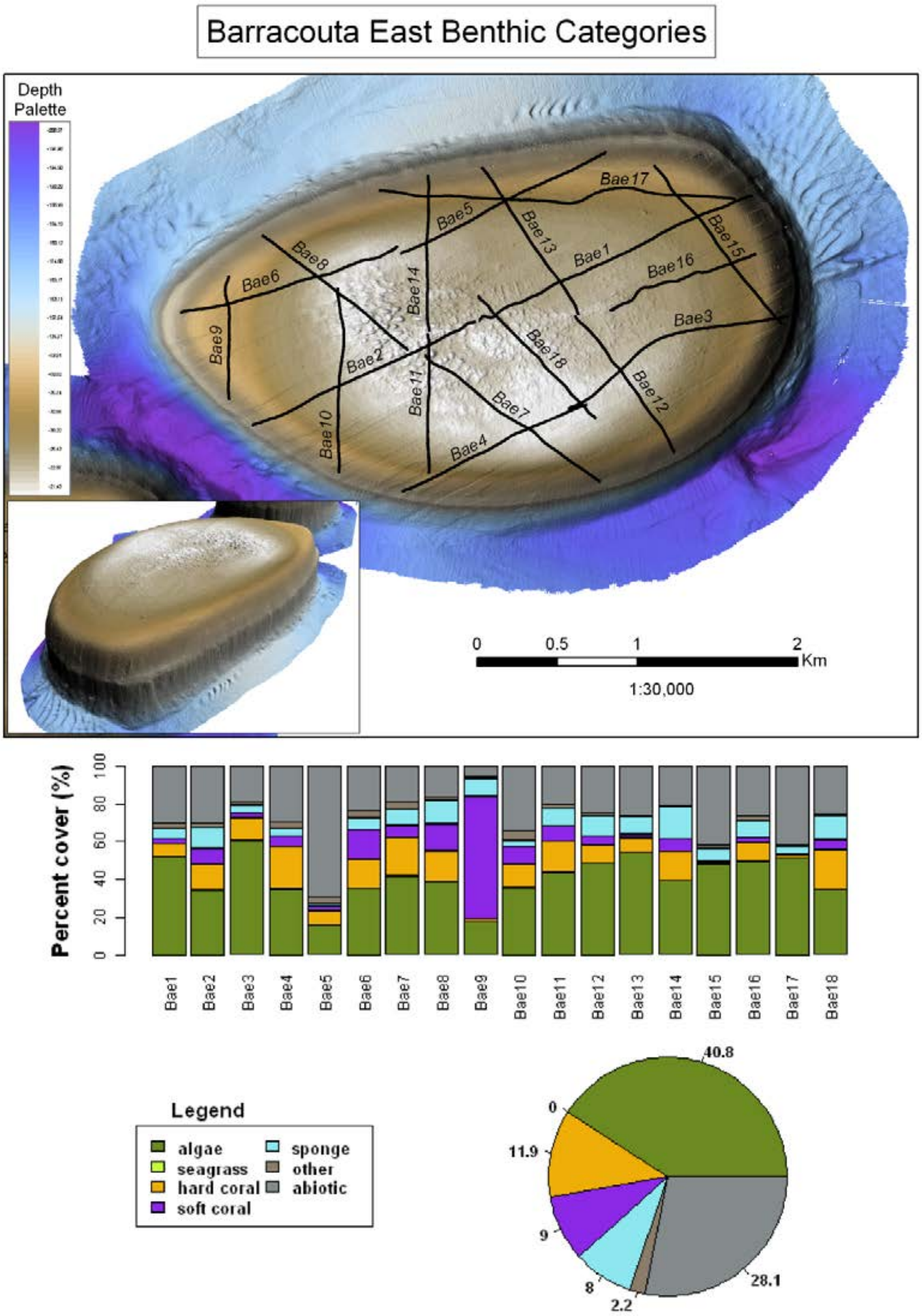

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Figure 3.8. Barracouta East shoal morphology, depth and the abundance (% cover) of major benthic groups derived from image analysis of high resolution still photos taken using the AIMS towvideo system along the sampling transects indicated by the seven black lines in the upper map. Data for individual transects is shown in the histogram and means for the shoal in the pie diagram.

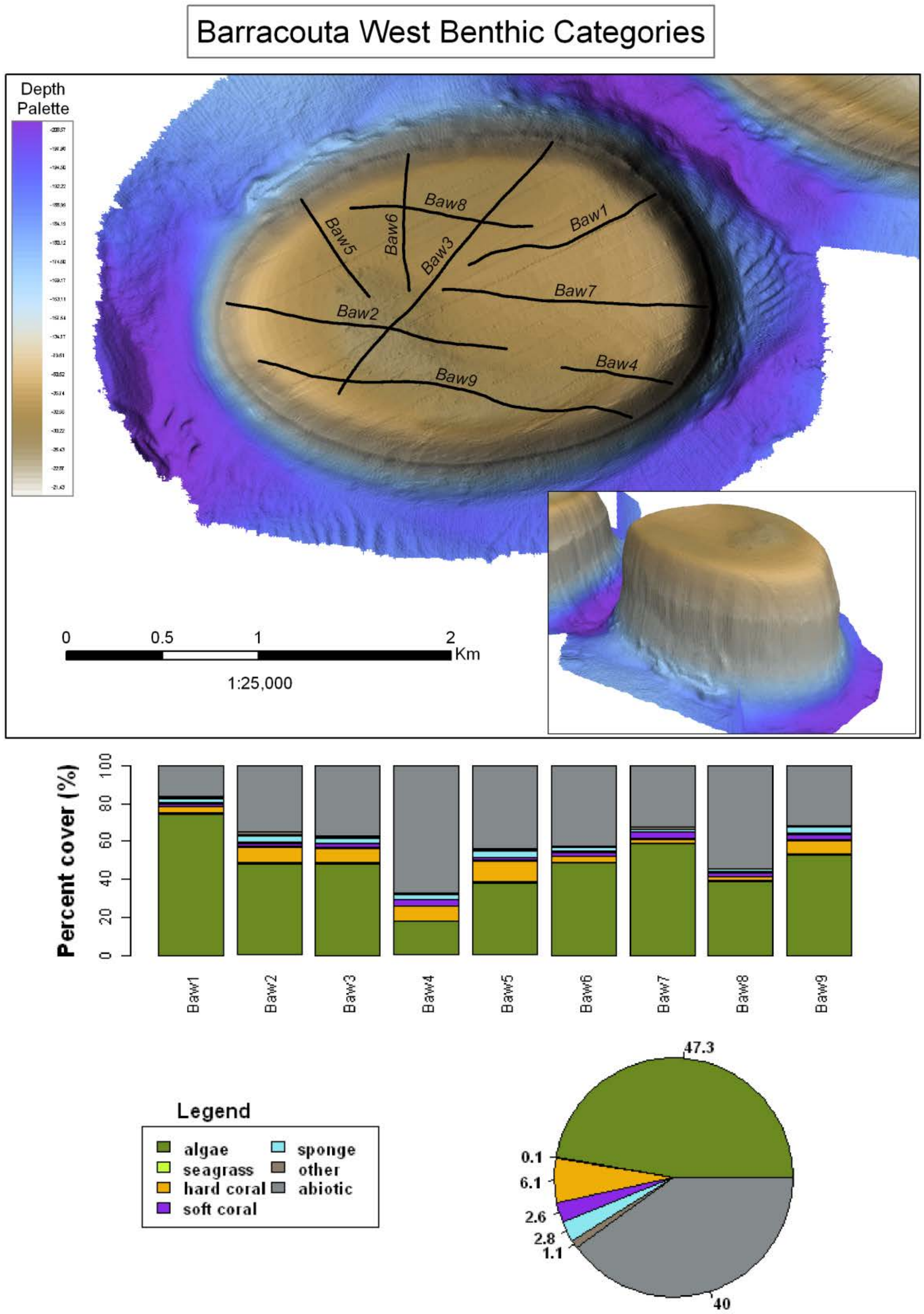


Figure 3.9. Barracouta West shoal morphology, depth and the abundance (% cover) of major benthic groups derived from image analysis of high resolution still photos taken using the AIMS towvideo system along the sampling transects indicated by the seven black lines in the upper map. Data for individual transects is shown in the histogram and means for the shoal in the pie diagram.

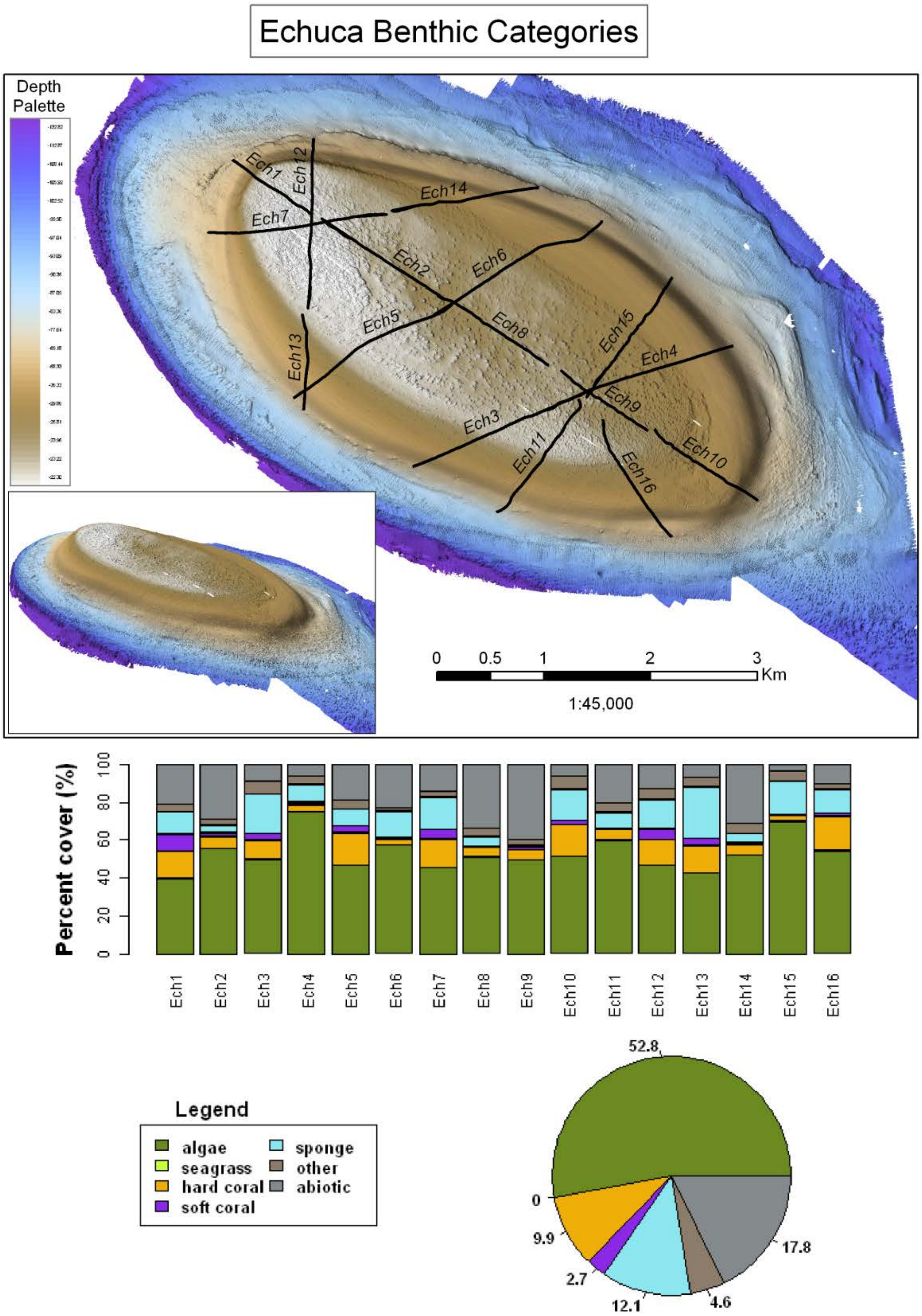


Figure 3.10. Echuca shoal morphology, depth and the abundance (% cover) of major benthic groups derived from image analysis of high resolution still photos taken using the AIMS towvideo system along the sampling transects indicated by the seven black lines in the upper map. Data for individual transects is shown in the histogram and means for the shoal in the pie diagram.

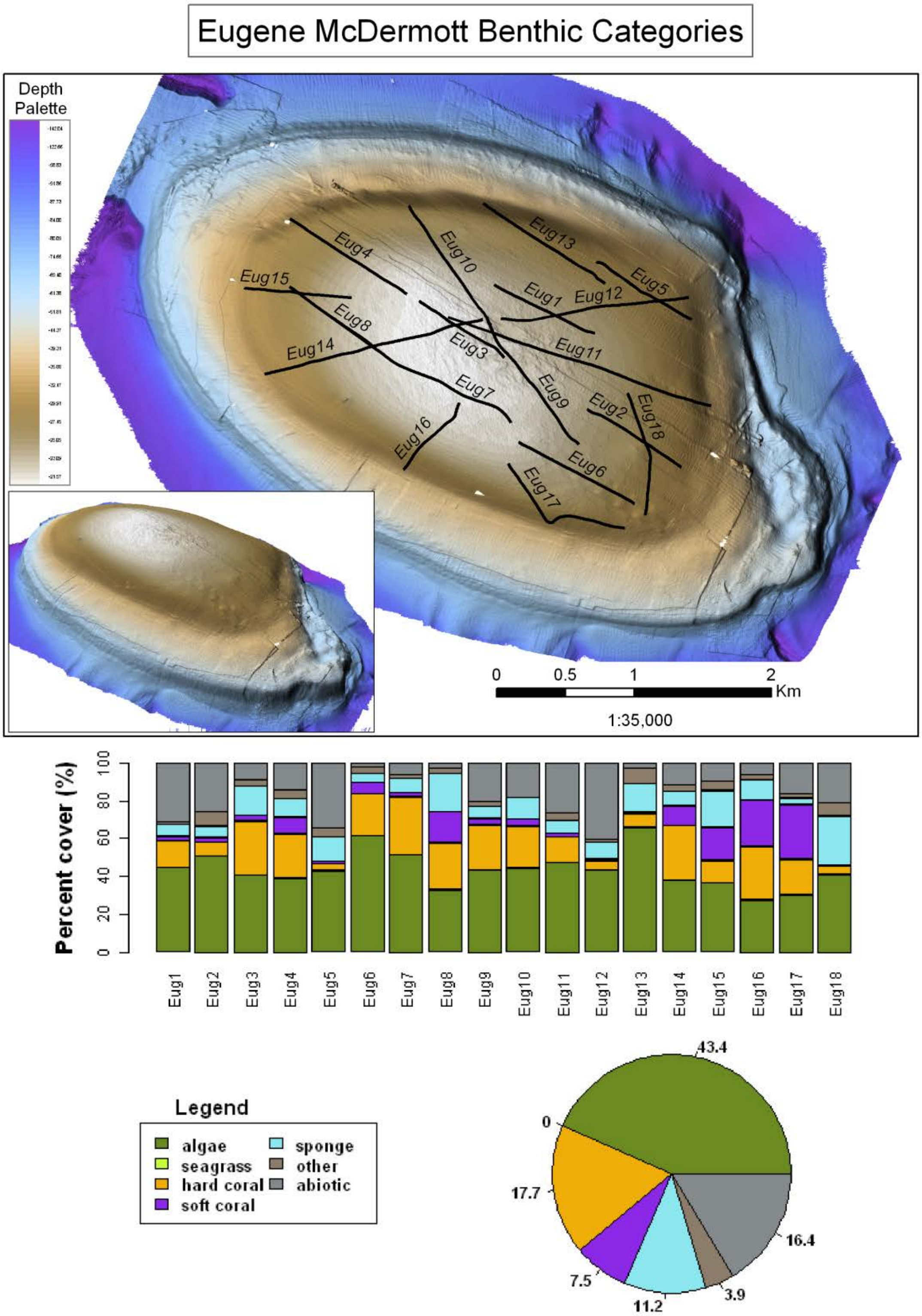


Figure 3.11. Eugene McDermott shoal morphology, depth and the abundance (% cover) of major benthic groups derived from image analysis of high resolution still photos taken using the AIMS towvideo system along the sampling transects indicated by the seven black lines in the upper map. Data for individual transects is shown in the histogram and means for the shoal in the pie diagram.

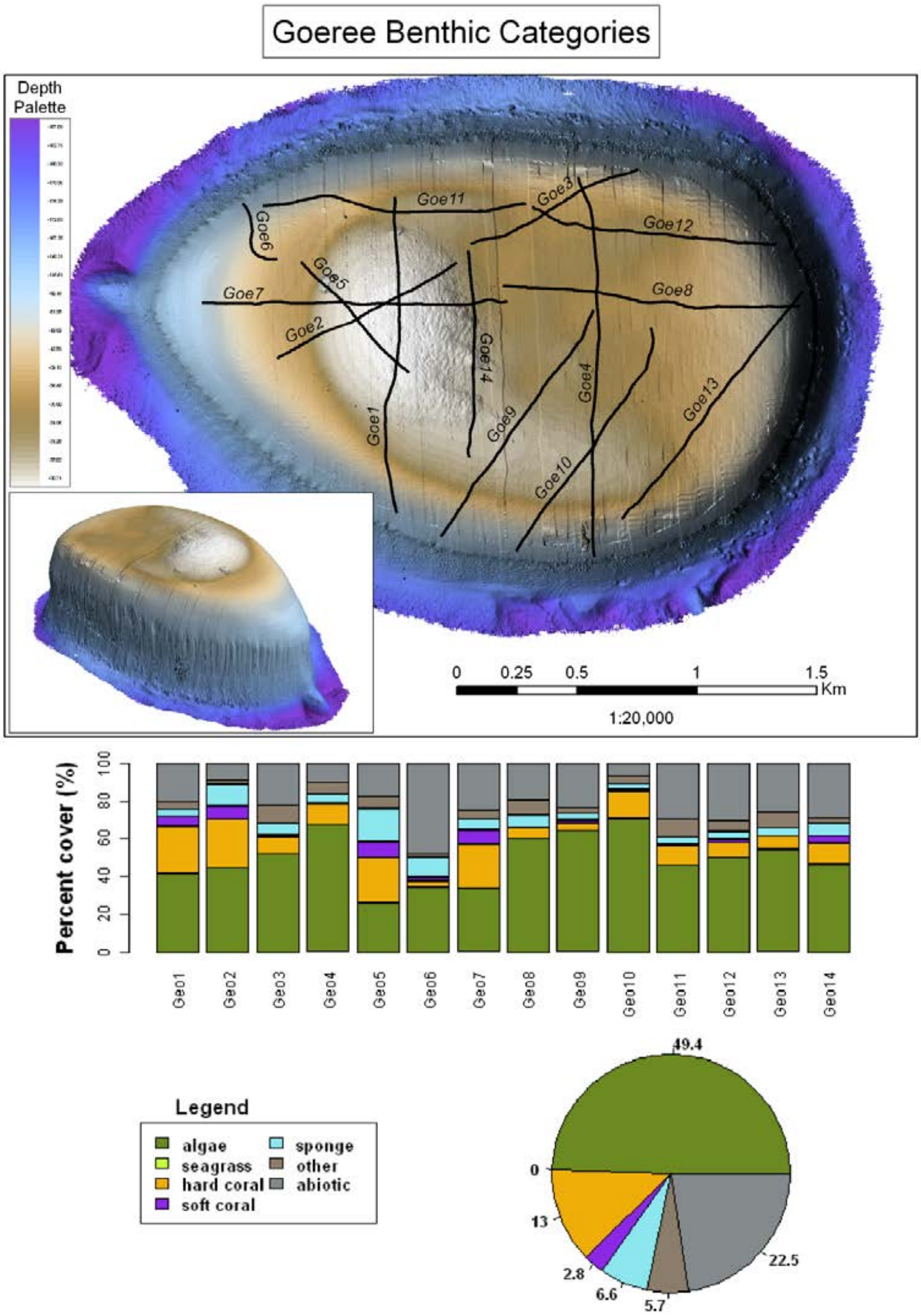


Figure 3.12. Goeree shoal morphology, depth and the abundance (% cover) of major benthic groups derived from image analysis of high resolution still photos taken using the AIMS towvideo system along the sampling transects indicated by the seven black lines in the upper map. Data for individual transects is shown in the histogram and means for the shoal in the pie diagram.

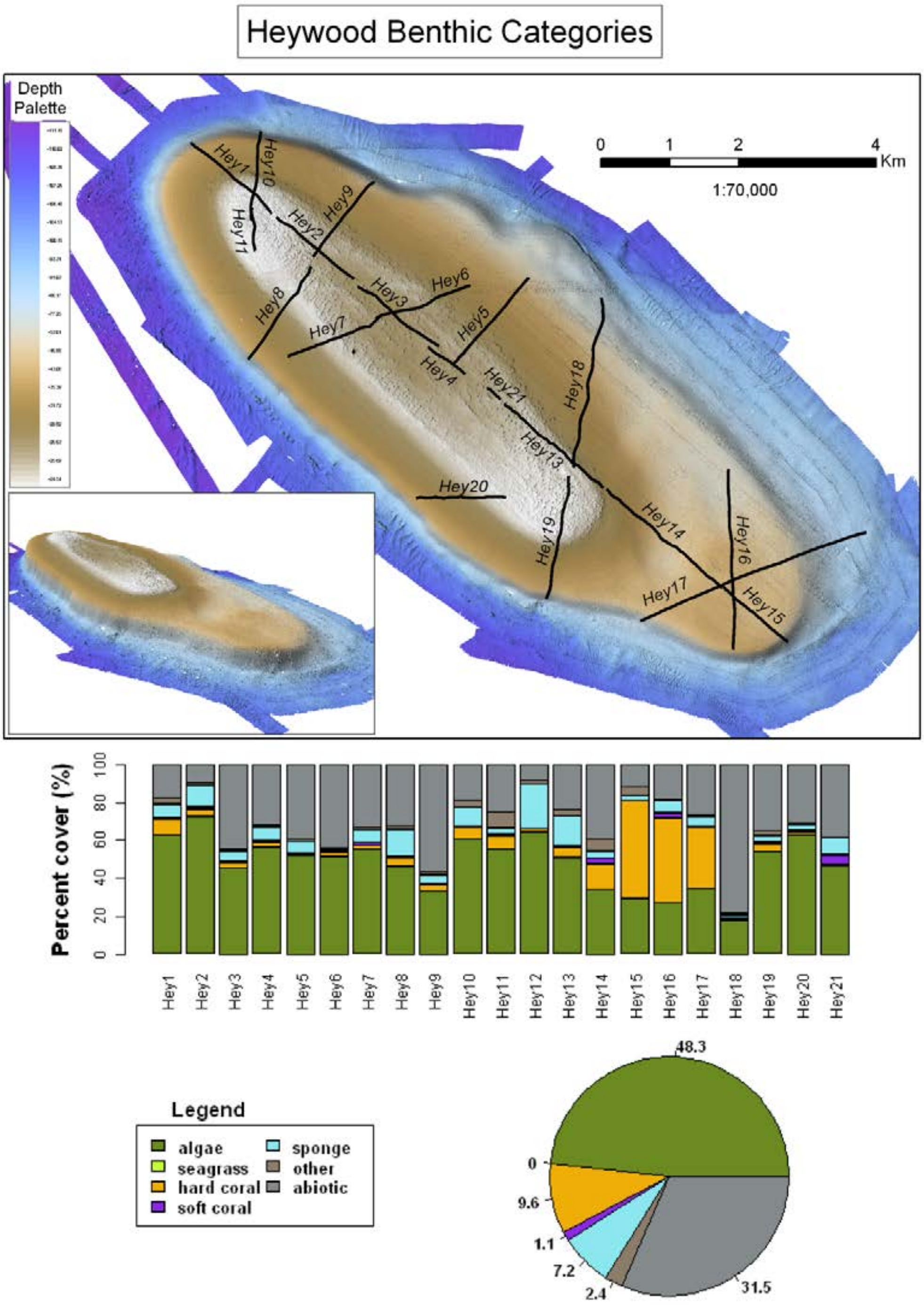


Figure 3.13. Heywood shoal morphology, depth and the abundance (% cover) of major benthic groups derived from image analysis of high resolution still photos taken using the AIMS towvideo system along the sampling transects indicated by the seven black lines in the upper map. Data for individual transects is shown in the histogram and means for the shoal in the pie diagram.

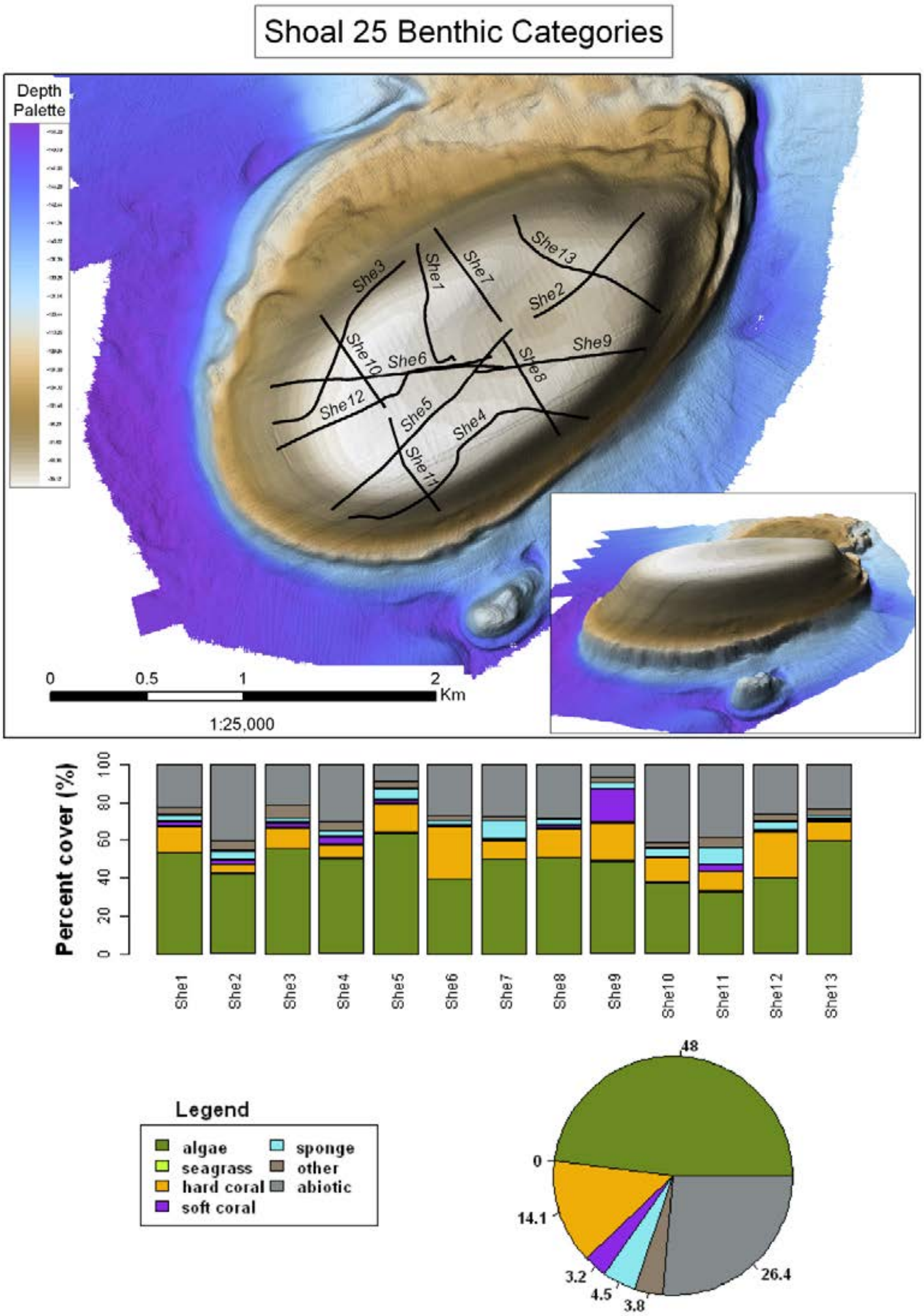


Figure 3.14. Shoal 25 morphology, depth and the abundance (% cover) of major benthic groups derived from image analysis of high resolution still photos taken using the AIMS towvideo system along the sampling transects indicated by the seven black lines in the upper map. Data for individual transects is shown in the histogram and means for the shoal in the pie diagram.

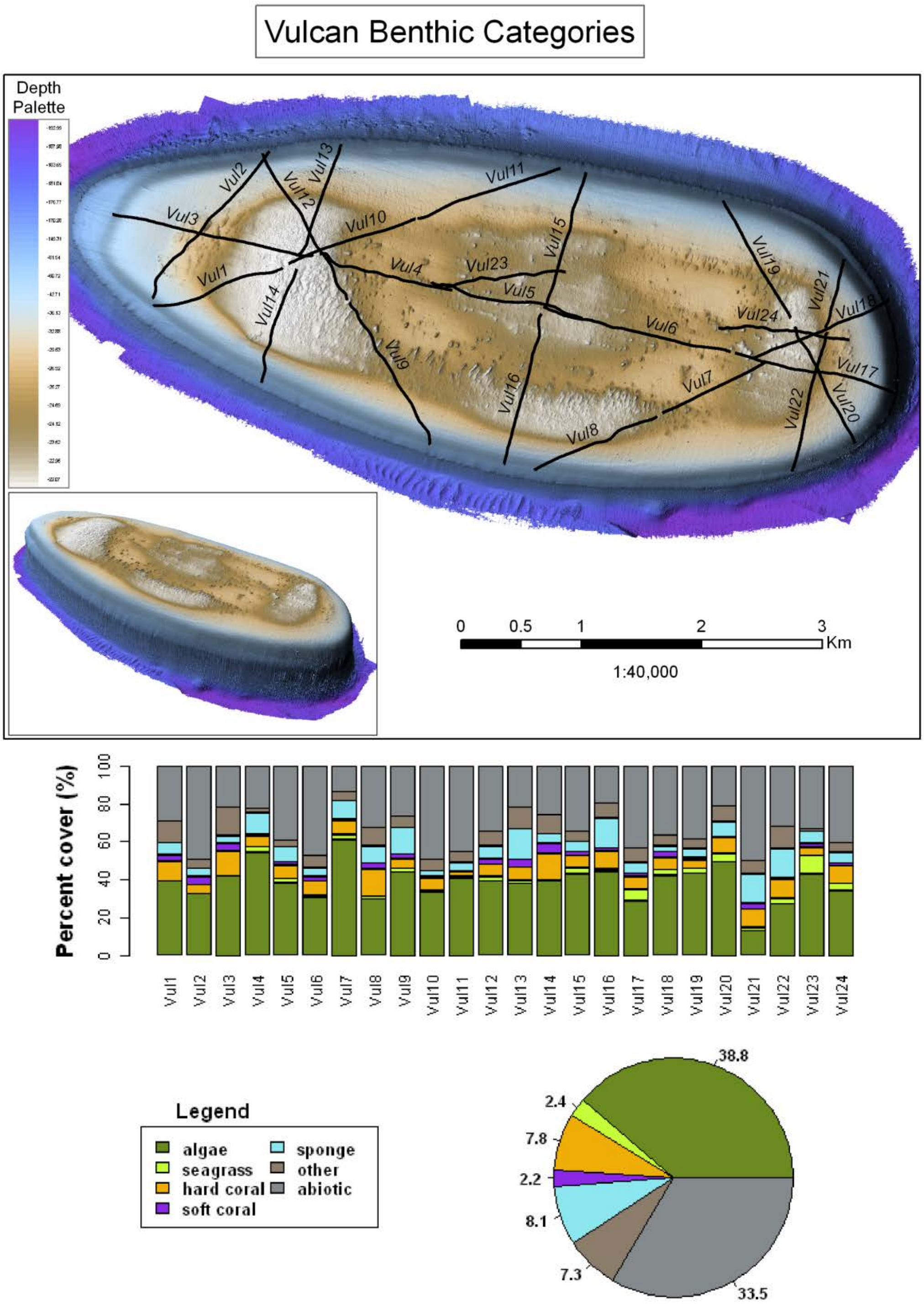


Figure 3.15. Vulcan shoal morphology, depth and the abundance (% cover) of major benthic groups derived from image analysis of high resolution still photos taken using the AIMS towvideo system along the sampling transects indicated by the seven black lines in the upper map. Data for individual transects is shown in the histogram and means for the shoal in the pie diagram.

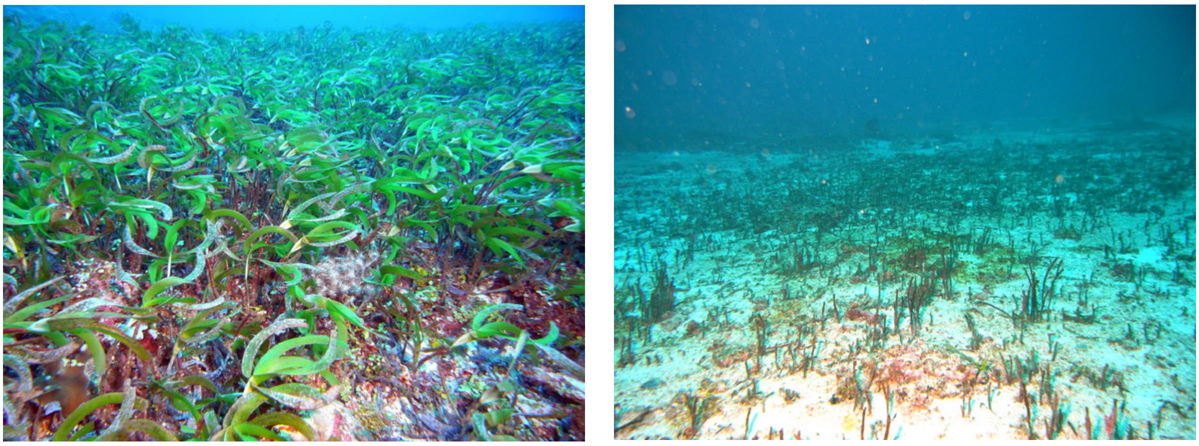


Figure 3.15.1 Vulcan Shoals seagrass change between 2010 and 2011. Image on the left was taken in April 2010. Image on the right taken in April 2011. Seagrass cover was extensive in 2010 and vestigial in 2011.

The two shoals surveyed in both 2010 and 2011, Barracouta and Vulcan, showed some changes in benthic cover between years. At Barracouta Shoal, there appeared to be a slight increase in algae and decrease in total live coral cover, although this may simply reflect the more extensive sampling undertaken in 2011. A much more dramatic change was observed at Vulcan Shoal, where the dense and extensive seagrass meadows seen in 2010 were gone in 2011, with only a field of rhizomes remaining (see Figure 3.15.1.) This highly significant change in seagrass cover may reflect a natural disturbance or a differential effect of the uncontrolled release, as the corals seemed healthy and slightly more abundant (Table 3.4). In 2010, mean seagrass cover at Vulcan Shoal was healthy in appearance and cover was 11.3%, reduced to 2.4% in the 2011 survey, which was composed nearly entirely of leafless rhizomes (Figure 3.15.1).

All shoals had the majority of seabed covered with life, ranging from 60-80%, with the remainder classed as Abiotic, often sand or bare rock and rubble. Various types of algae were the most abundant lifeform, followed usually by hard coral and sponges. Most major coral families were represented on all shoals, with Acroporidae and Poritidae most common, except at the towed deepest shoals Shoal 25 and Wave Governor Bank, where Fungiidae were the most important coral family (Figure 3.16).

Table 3.4. General linear model comparing cover for benthic groups using all Vulcan Shoal photo survey transects 2010-2011

	Estimate	Std. Error	t value	Pr(>|t|)
Abiotic	-0.02958	0.17578	-0.168	0.867
Algae	0.80826	0.11898	6.793	3.23E-08
Hard Coral	0.2221	0.1939	1.145	0.259
Other	-0.6828	0.1804	-3.784	0.000494
Seagrass	-1.6435	0.4381	-3.751	0.000545
Soft Coral	0.3871	0.2458	1.575	0.123

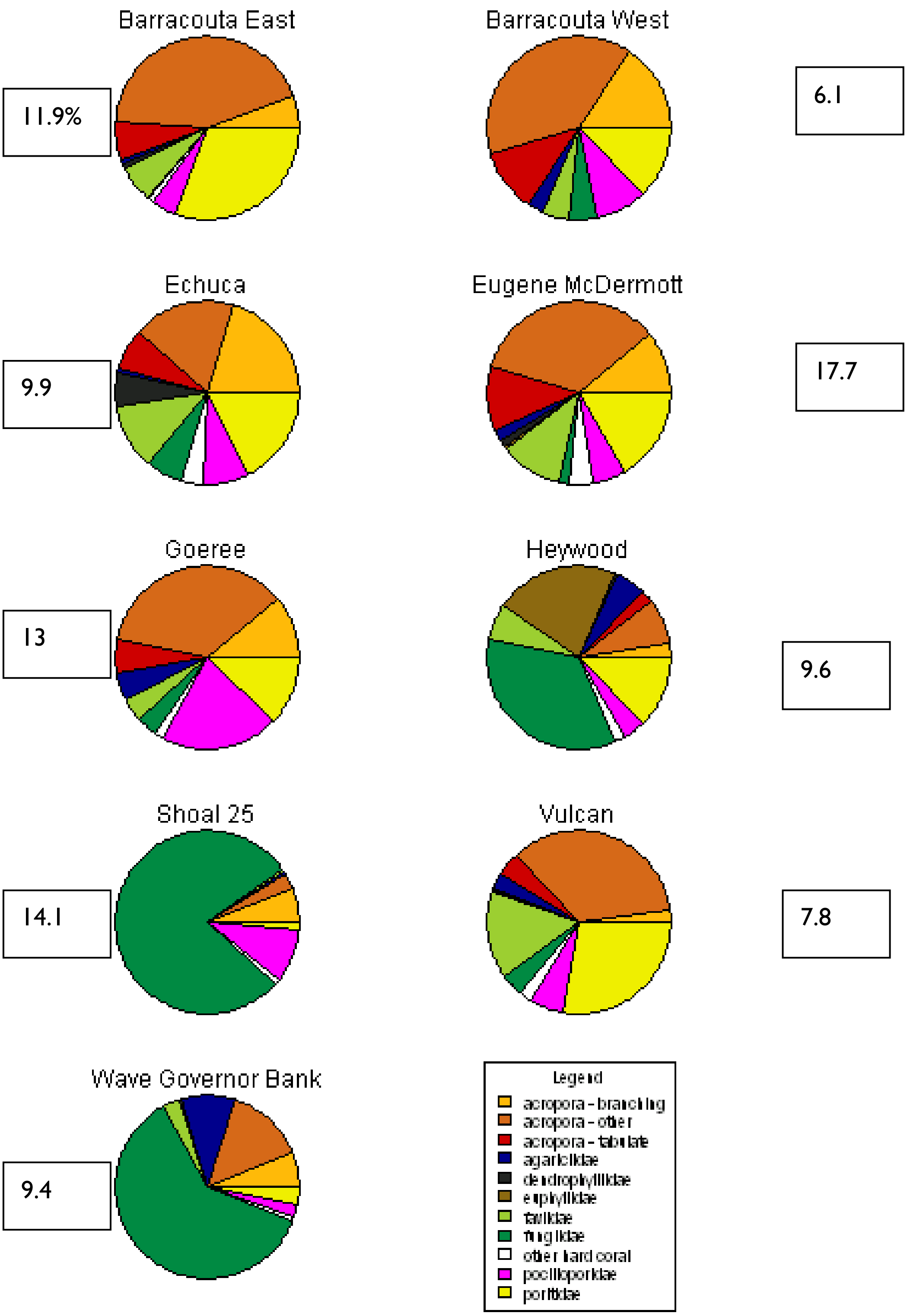


Figure 3.16. Relative hard coral composition for major taxonomic categories on all shoals. Categories were included when they were >1% of the cover across all transects. Total mean coral cover for each shoal is shown in the box adjacent to each pie diagram. Coral cover at each shoal relative to other major benthic groups is provided in Figures 3.7-3.15.

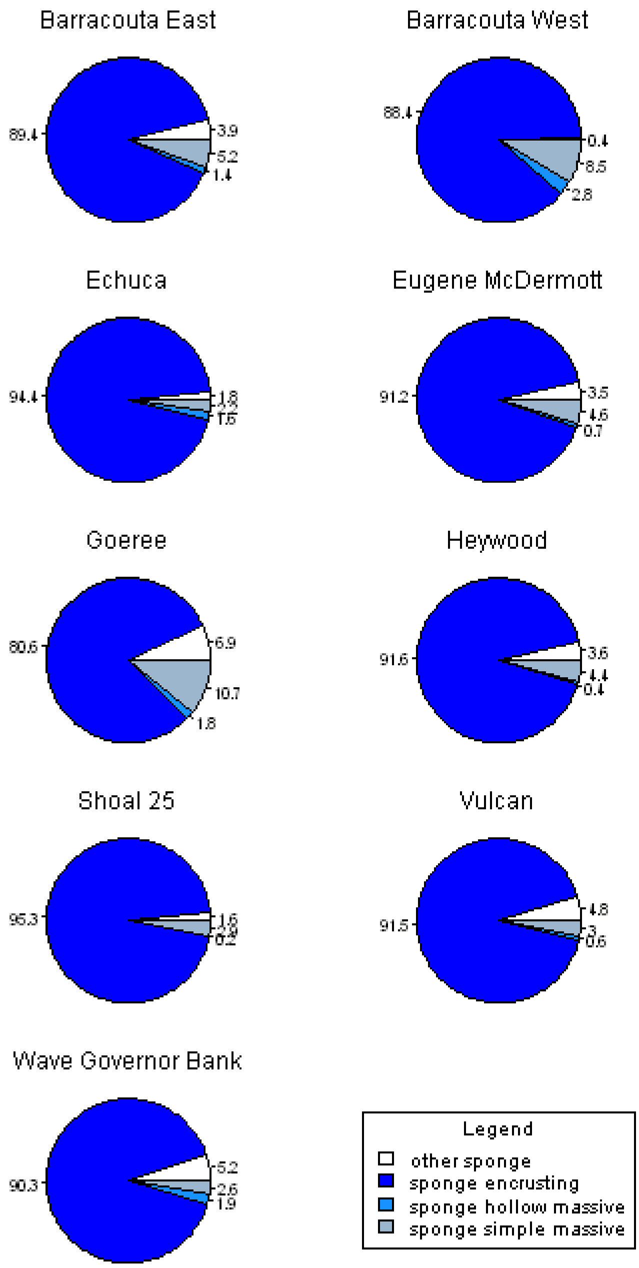


Figure 3.17. Relative sponge composition for major morphological categories on all shoals. Categories were included when they were >1% of the cover across all transects. Total mean sponge cover and abundance at each shoal relative to other major benthic groups is provided in Figures 3.7-3.15.

The sponges were represented, in terms of benthic % cover, overwhelmingly by encrusting forms (Figure 3.17) at all shoals, with simple massive and other forms contributing around 10% of the total sponge cover. Algae were represented in relative abundance mostly by a mix of turf, crustose coralline red algae and *Halimeda*, with red fleshy macroalgae also ubiquitous but of lesser importance (Figure 3.18).

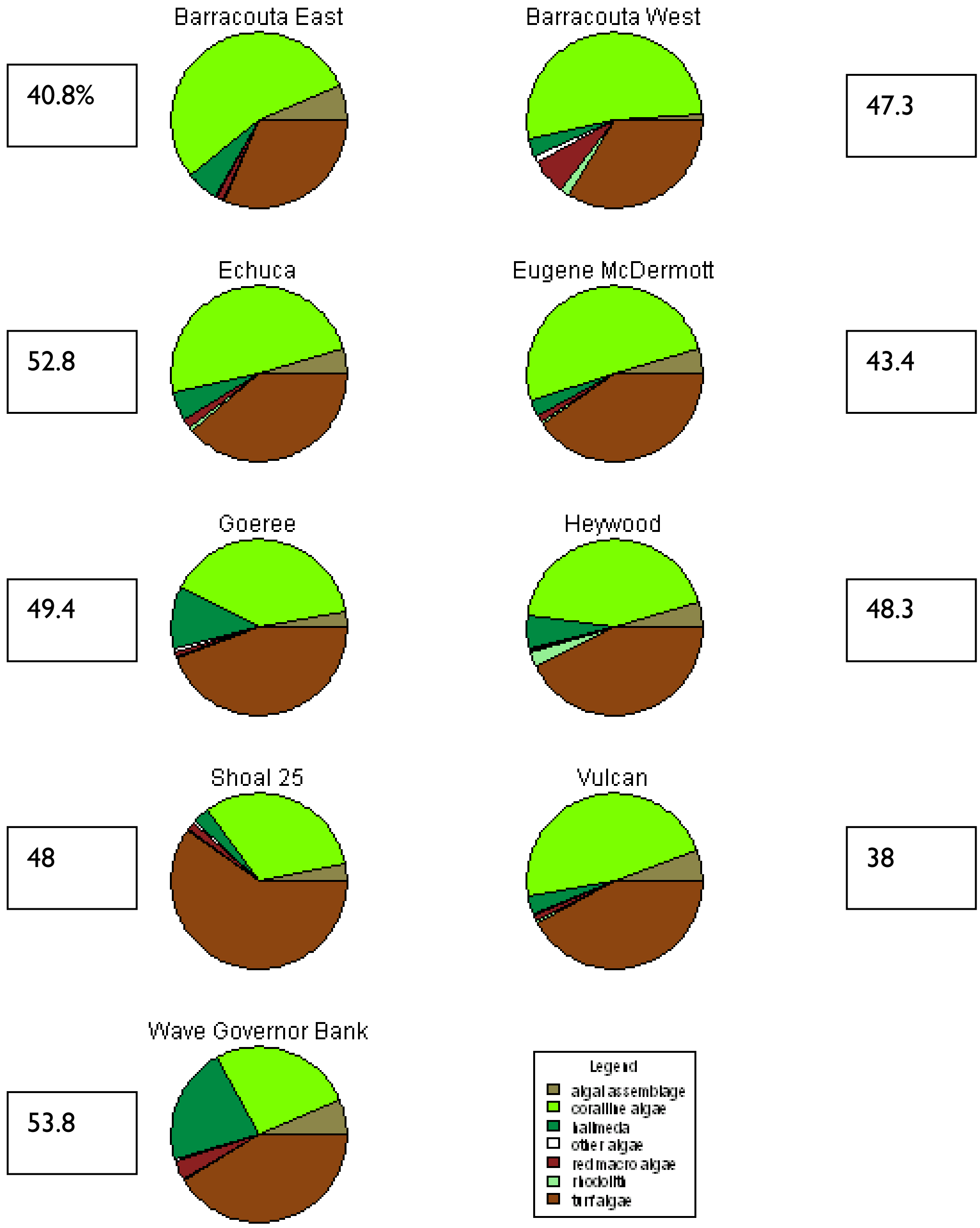


Figure 3.18. Relative algal composition for major categories on all shoals. Categories were included when they were **≥1% of the cover across all transects except. T**otal mean algal cover for each shoal is shown in the box adjacent to each pie diagram. Algal cover at each shoal relative to other major benthic groups is provided in Figures 3.7-3.15.

The patterns of major benthos varied between shoals, mainly in the relative importance of each group. A cluster analysis using the towvid broadscale habitat classification data shows two main groups of shoals (Figure 3.19). Three of which Heywood, Barracouta East and Vulcan, cluster together, driven mostly by the presence of similar Hard Coral/Soft coral/*Halimeda* habitat. This group represents both high and low exposure shoals.

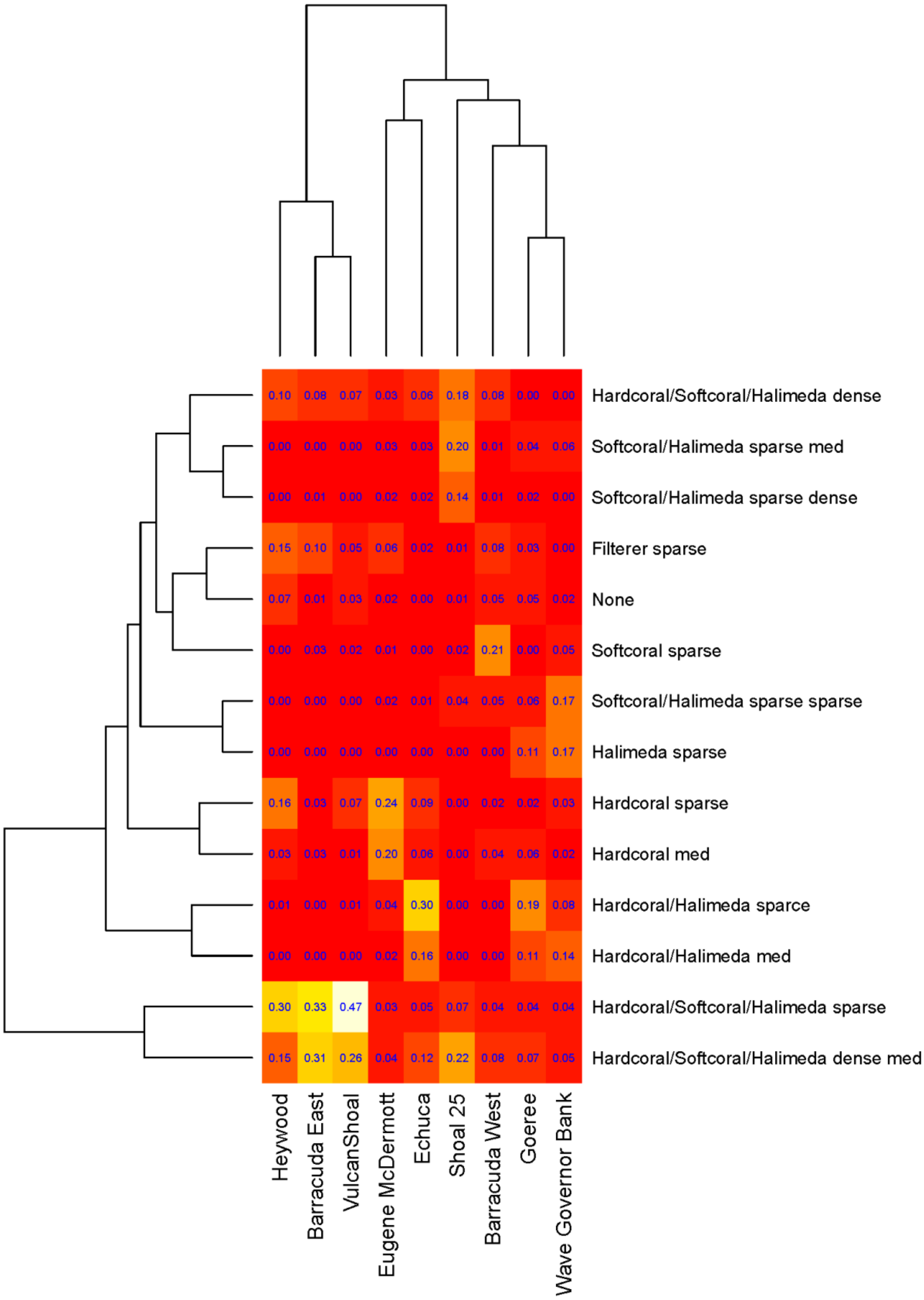


Figure 3.19. Cluster analysis of similarities between shoals for major benthic groups. To aid interpretation of these patterns, each cluster has also been expressed in association with a heatmap, labelled with proportion of cover for each major benthic group at an individual shoal. This provides a visual tool with which to quickly identify shoals or groups of shoals which group together because of one or more of the major benthic groups. In the heat map matrix, the cells have been coloured coded from dark red, which is low benthic cover, to yellow/white, which is high benthic cover.

3.4.2 Benthic habitat and substrate models

From the AUC statistics model, predictive and discriminative performance was very good for all biotic and substrate categories. This translated into classification accuracy averaging 79% (range from 66% to 98%, see Table 3.4).

For each shoal the resulting maps including a) composite habitat maps for major biota groups, and b) major substrate types, are shown in Figures 3.21-3.22 For Barracouta East Shoal, Figures 3.23-3.24 for Barracouta West Shoal, Figures 3.25-3.26 for Euchuca Shoal, Figure 3.27-3.28 for Eugene McDermott Shoal, Figure 3.29-3.30 for Goree Shoal, Figure 3.31-2.32 for Heyward Shoal, Figure 3.33-3.34 for Shoal 25, Figure 3.35-3.36 for Vulcan Shoal and Figure 3.37-3.38 For Wave Governors Bank.

Probability maps of sensitive habitat including a) live hard coral and b) Halimeda are shown in Figures 3.39 for Barracouta East Shoal, Figures 3.40 for Barracouta West Shoal, Figures 3.41 for Euchuca Shoal, Figure 3.42 for Eugene McDermott Shoal, Figure 3.43 for Goree Shoal, Figure 3.44 for Heyward Shoal, Figure 3.45 for Shoal 25, Figure 3.46 for Vulcan Shoal and Figure 3.47 For Wave Governors Bank.

Multibeam derived environmental correlates of biotic and substrate distribution were dominated by response to depth gradients, broad scale rugosity variation and aspect. For example, see Figures 3.20 and Appendix 3C (note hyp50 is the broad scale rugosity variable and aspect is in integer radian catagories).

For the biotic groups, hard corals (Figure 3.20) showed greater prevalence at depths less than 30 m or in some cases greater than 40 m (however with lower abundance). Hard corals were also correlated with areas of high rugosity (see hyp50, Figure 3.20) and more likely to be present on the northern tip (radian groups 1 and 6, Figure 3.20) of shoals rather than shoal edges (radian groups 2,3,4,5, Figure 3.20). Filter feeders and soft coral has similar patterns of distribution, (see Figures C3.1 and C3.2 respectively) their likelihood of occurrence increased significantly in water deeper than 30 m, with higher levels of broad scale rugosity and generally inhabited the shoal sides. *Halimeda* and other macroalage (Figure C3.4 and C3.5 respectively) had similar depth preferences to soft coral and filter feeders (increasing occurrence in water deeper than 40 m. *Halimeda* had more of a preference for areas of higher rugosity (hyp50, Figure C3.4) which differs from other macroalgae. Macroalgae is most commonly found on the north eastern sides of shoals (radian groups 0-2, Figure C3.5) where *Halimeda* are more commonly found along the south east and south west of shoals (radian groups 2-5, Figures C3.4 and C3.5).

For the abiotic groups, high relief and low relief limestone (Figures C3.6 and C3.7) had similar responses. Both occurred more frequently in depths less than 40 m and were correlated with areas of high rugosity. The distribution of rubble and stone mixed with rubble (Figure C3.8 and C3.9) both had specific depth profiles, with bands of high and low occurrence from 20 to 50 m. They were also associated with medium to low broad scale (hyp 50) rugosity. Sand had very specific depth banding and occurred in areas of low broad scale rugosity (hyp 50 between 0.1-0.4) (Figure C3.10). Sand and rubble distribution (Figure C3.11) was most strongly correlated with increasing depth, but also bands of low (0-0.1, 0.3-0.5) broadscale rogosity (Hyp 50, Figure 3.11). Course sand (Figure C3.12) had banded association with depths greater than 50 m or between 30-40 m. Its likelihood of occurrence increased with broadscale rugosity.

Table 3.5. Biotic and substrate predicted presence absence models

Model	AUC	Probability cut-off	sensitivity	specificity	% correct	Kappa
Hard Coral	0.87	0.31	0.82	0.89	86.3%	0.48
Filter Feeders	0.91	0.04	0.78	0.87	87.2%	0.19
Soft Coral	0.89	0.08	0.92	0.70	71.6%	0.23
Isolates	0.94	0.01	0.97	0.79	79.1%	0.08
Halimeda	0.91	0.08	0.89	0.77	77.8%	0.24
Macroalgae	0.99	0.01	0.95	0.96	96.2%	0.14
High relief limestone	0.86	0.17	0.86	0.73	74.7%	0.39
Low relief limestone	0.78	0.25	0.80	0.62	66.4%	0.30
Rubble	0.76	0.21	0.58	0.80	76.1%	0.30
Rubble/Stone	0.76	0.15	0.73	0.65	65.8%	0.22
Sand Coarse	0.93	0.08	0.91	0.80	80.9%	0.31
Sand/Rubble	0.83	0.27	0.81	0.70	72.6%	0.39
Sand Waves	0.99	0.01	1.00	0.98	98.2%	0.03

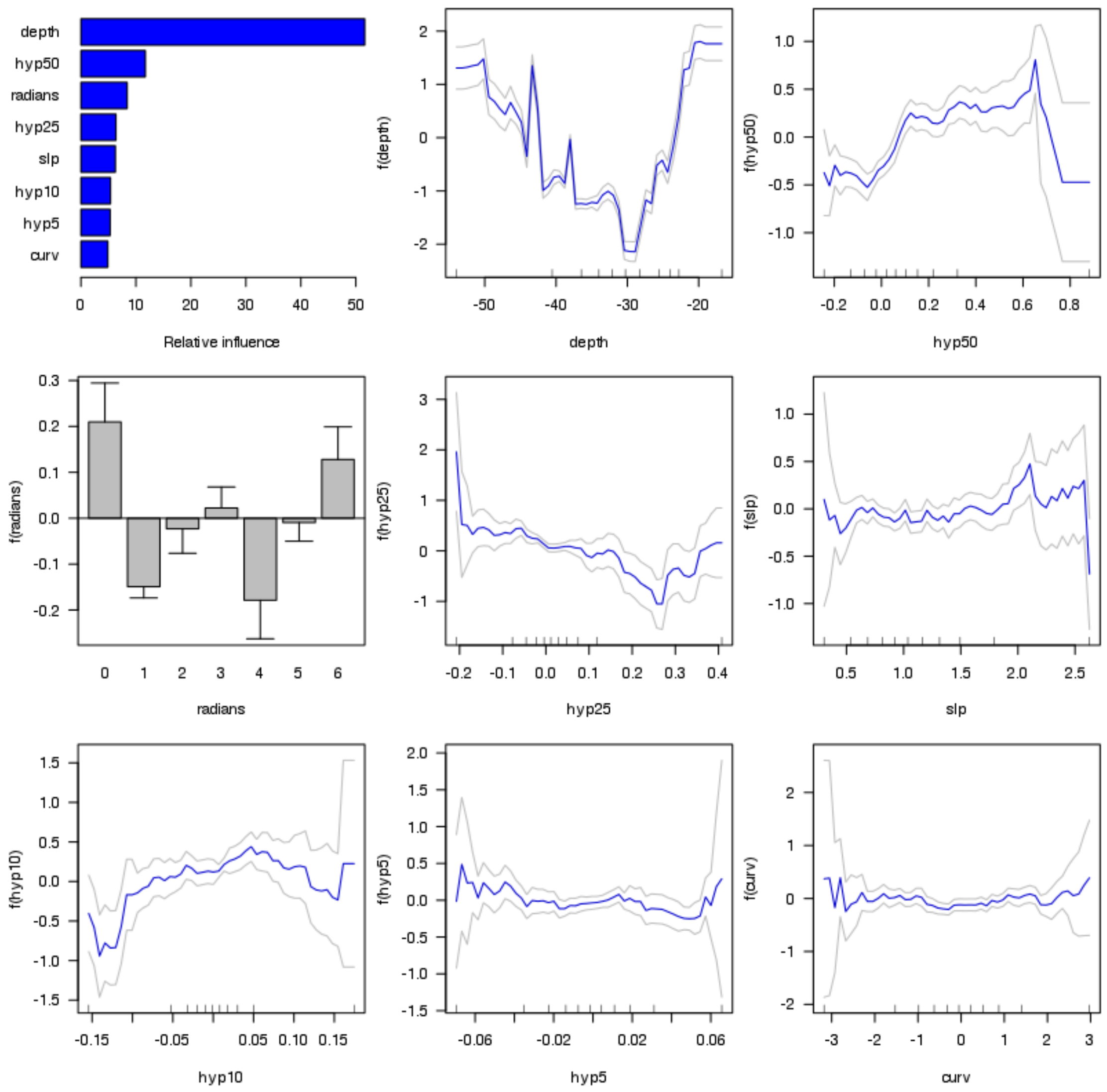


Figure 3.20. Hard coral partial response plots. Y-axis are mean centered probability of occurrence. For details or response variables see Table 3.1 See remainder of these plots in Appendix 3C.

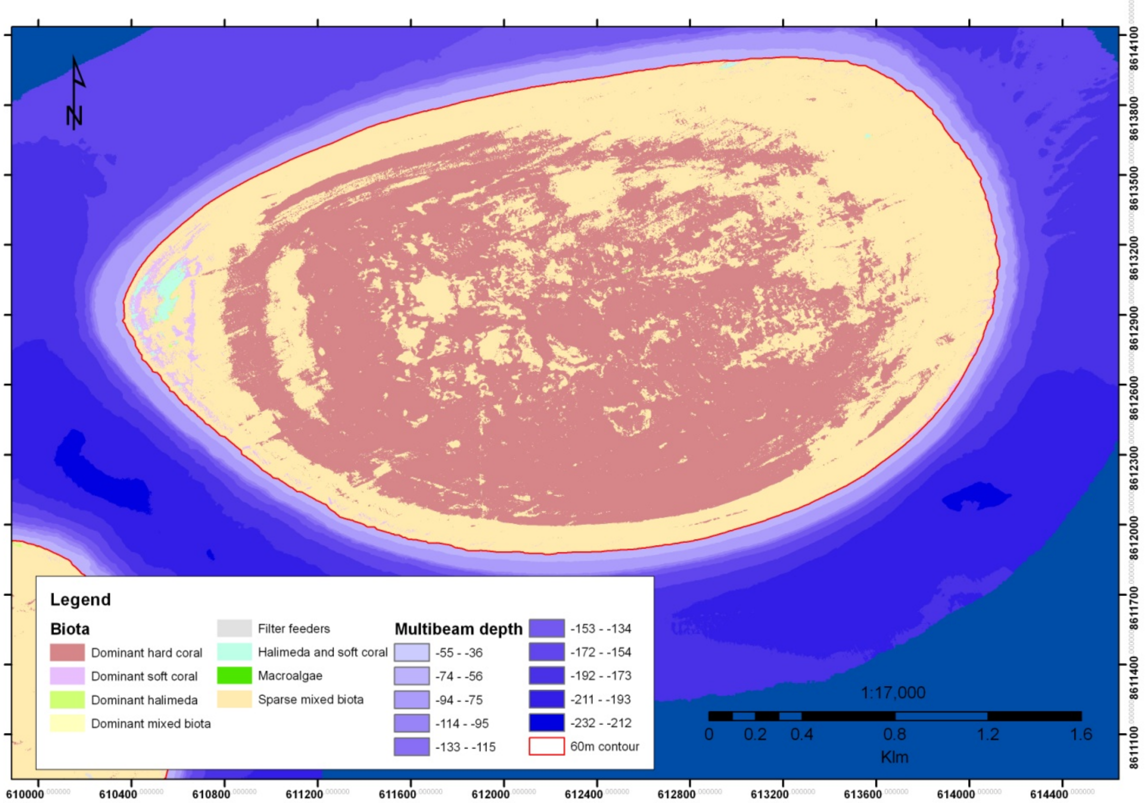


Figure 3.21. Composite biotic habitat map Barracouta East.

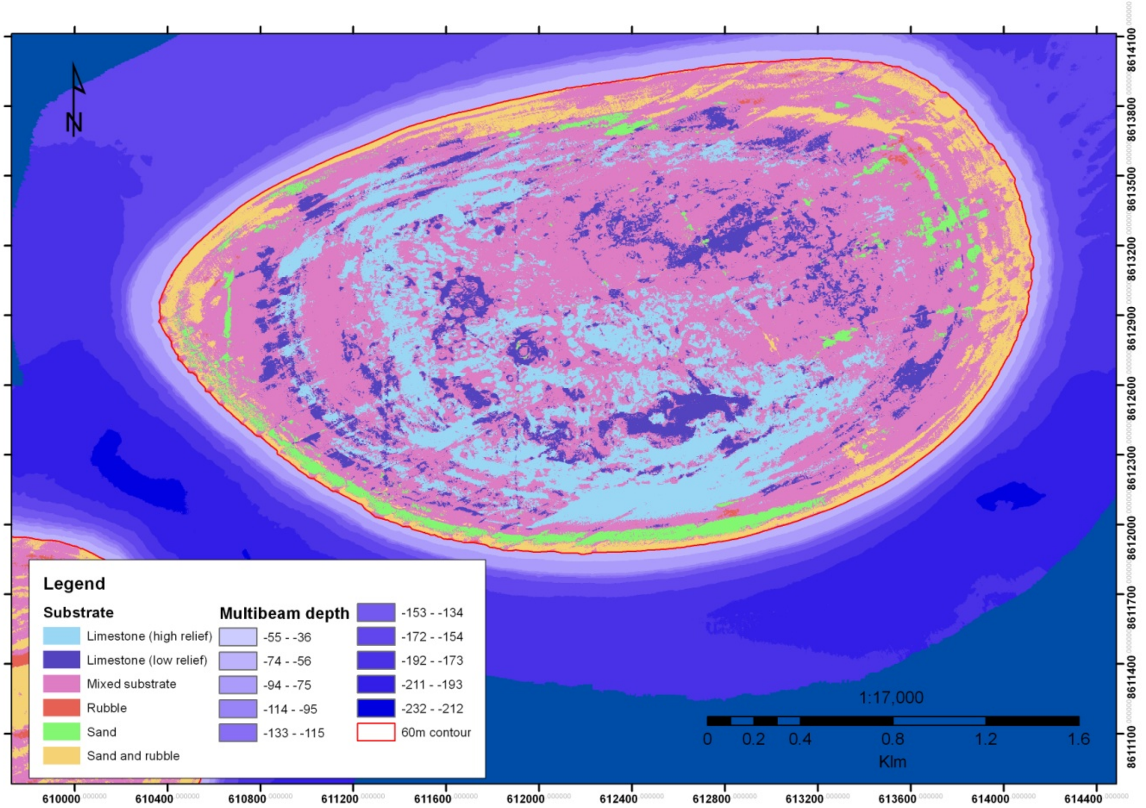


Figure 3.22. Substrate habitat map Barracouta East.

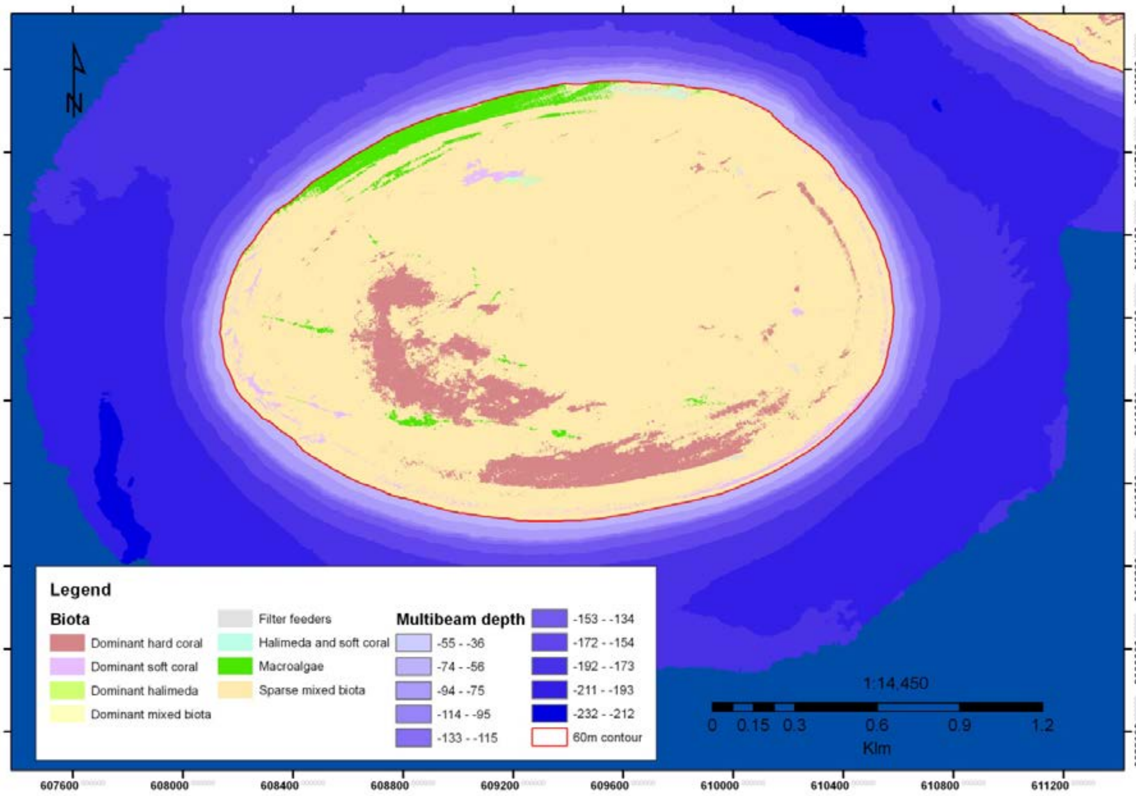


Figure 3.23. Composite biotic habitat map Barracouta West.

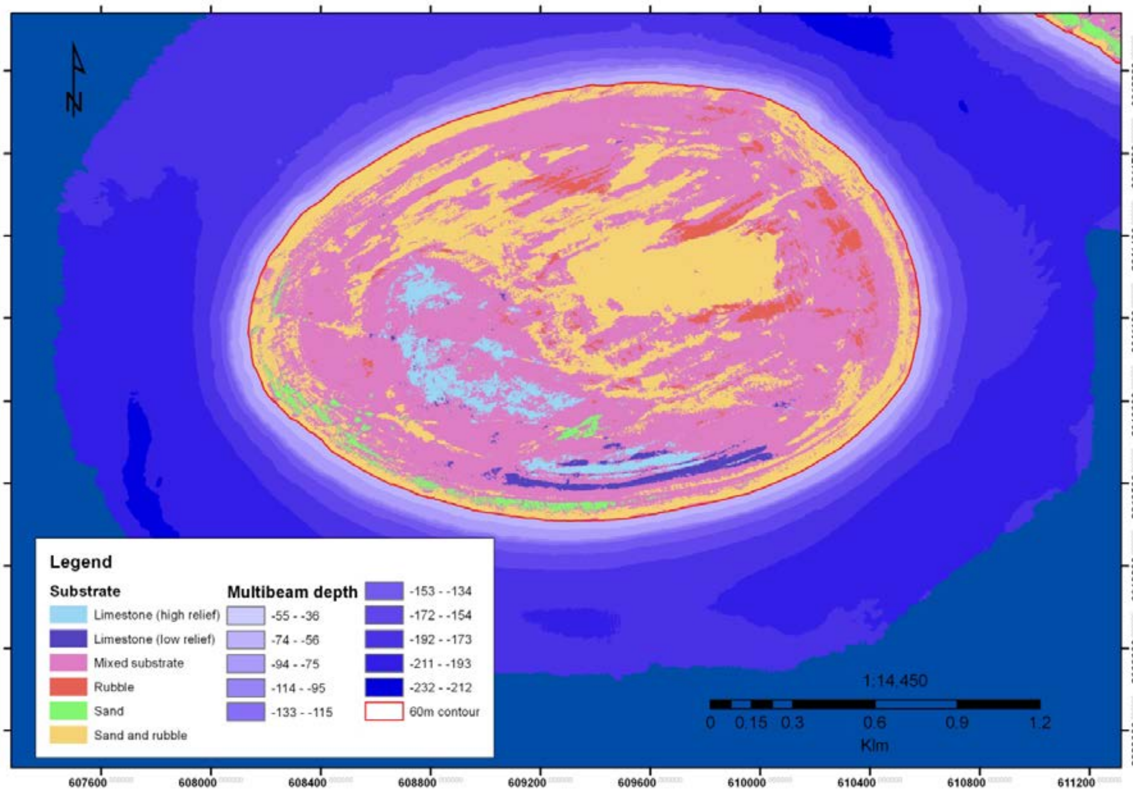


Figure 3.24. Substrate habitat map Barracouta West.

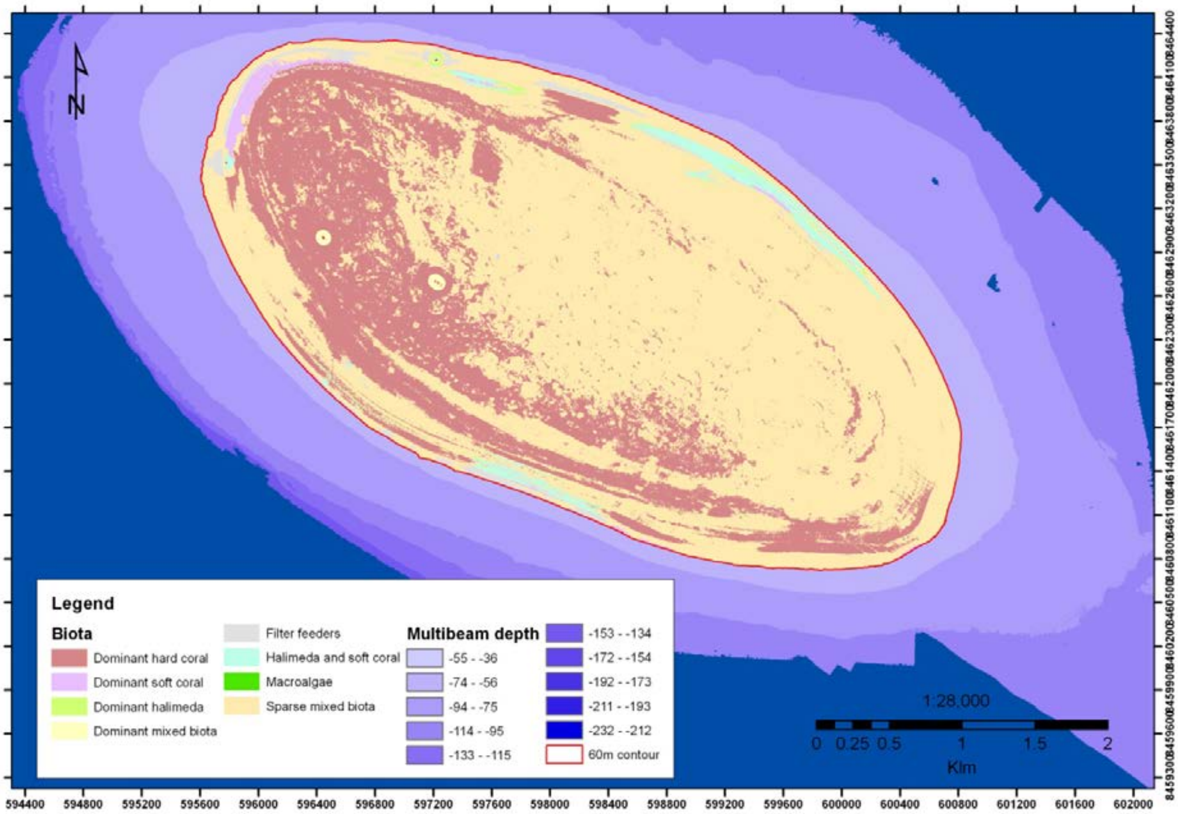


Figure 3.25. Composite biotic habitat map Echuca Shoal.

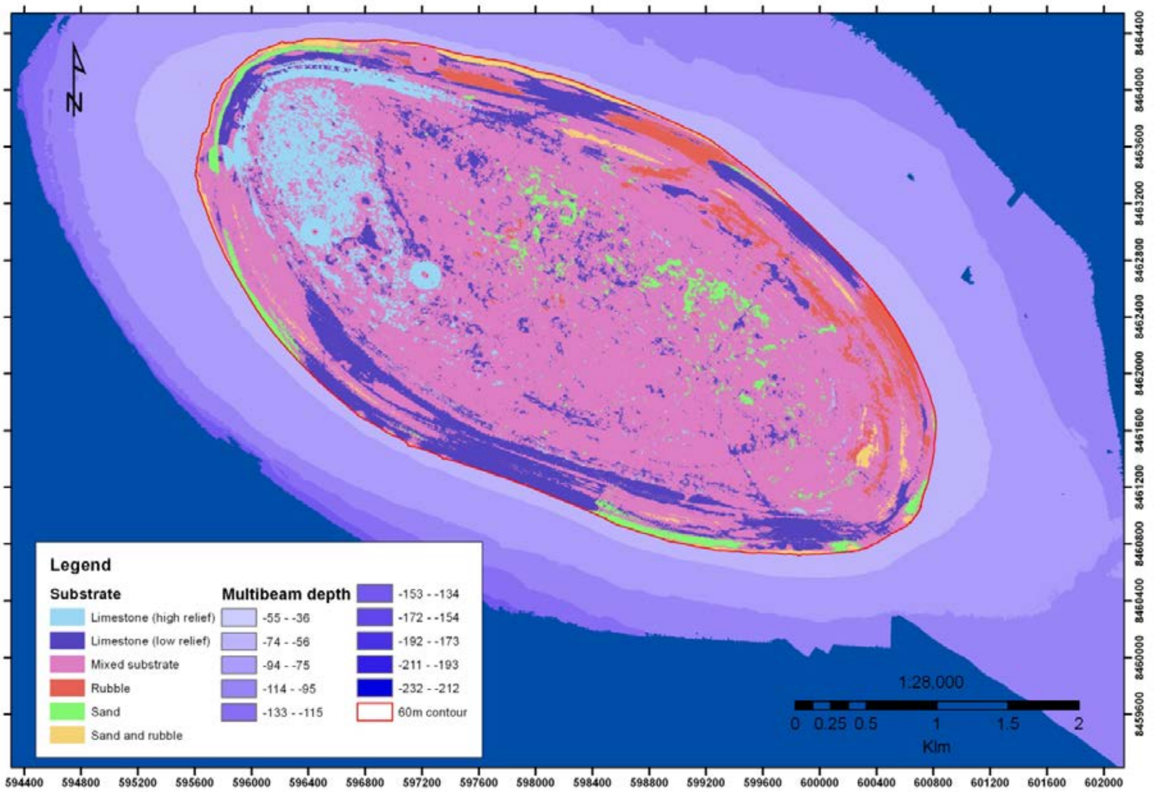


Figure 3.26. Composite substrate habitat map Echuca Shoal.

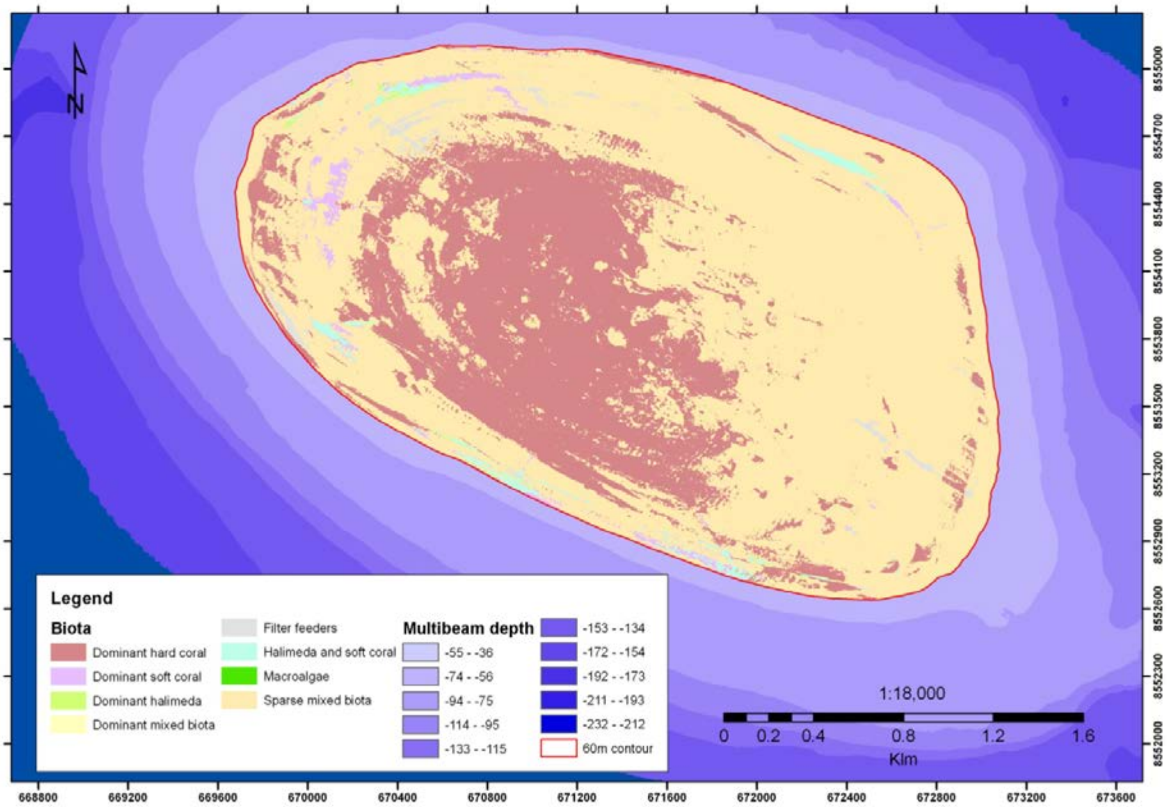


Figure 3.27. Composite biota habitat map Eugene McDermott Shoal.

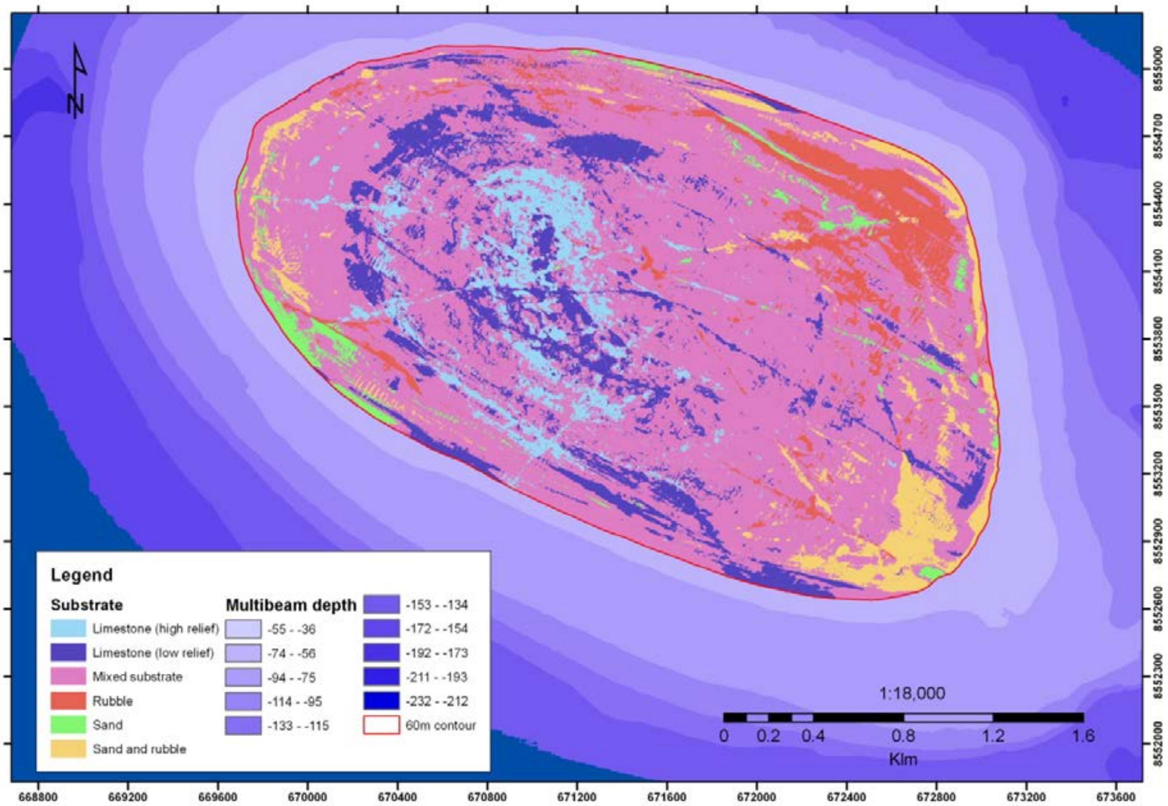


Figure 3.28. Composite substrate habitat map Eugene McDermott Shoal.

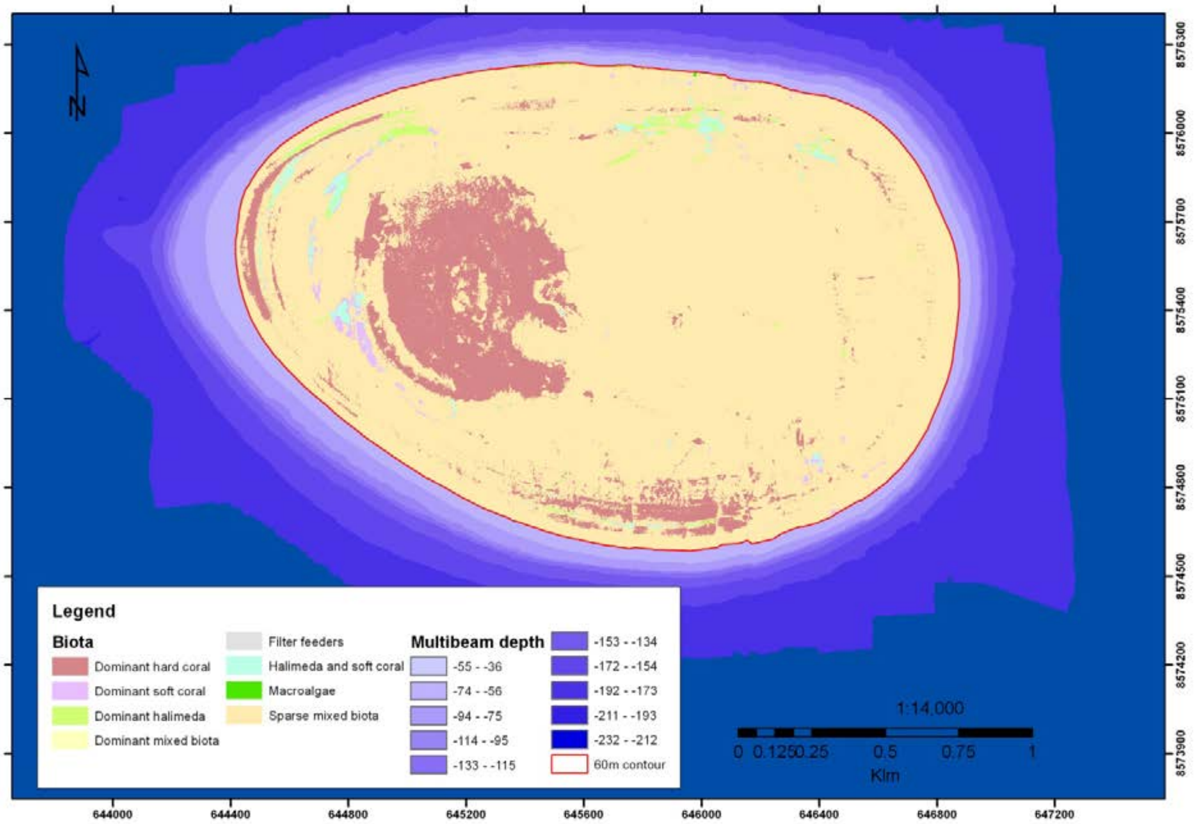


Figure 3.29. Composite biotic habitat map Goeree Shoal.

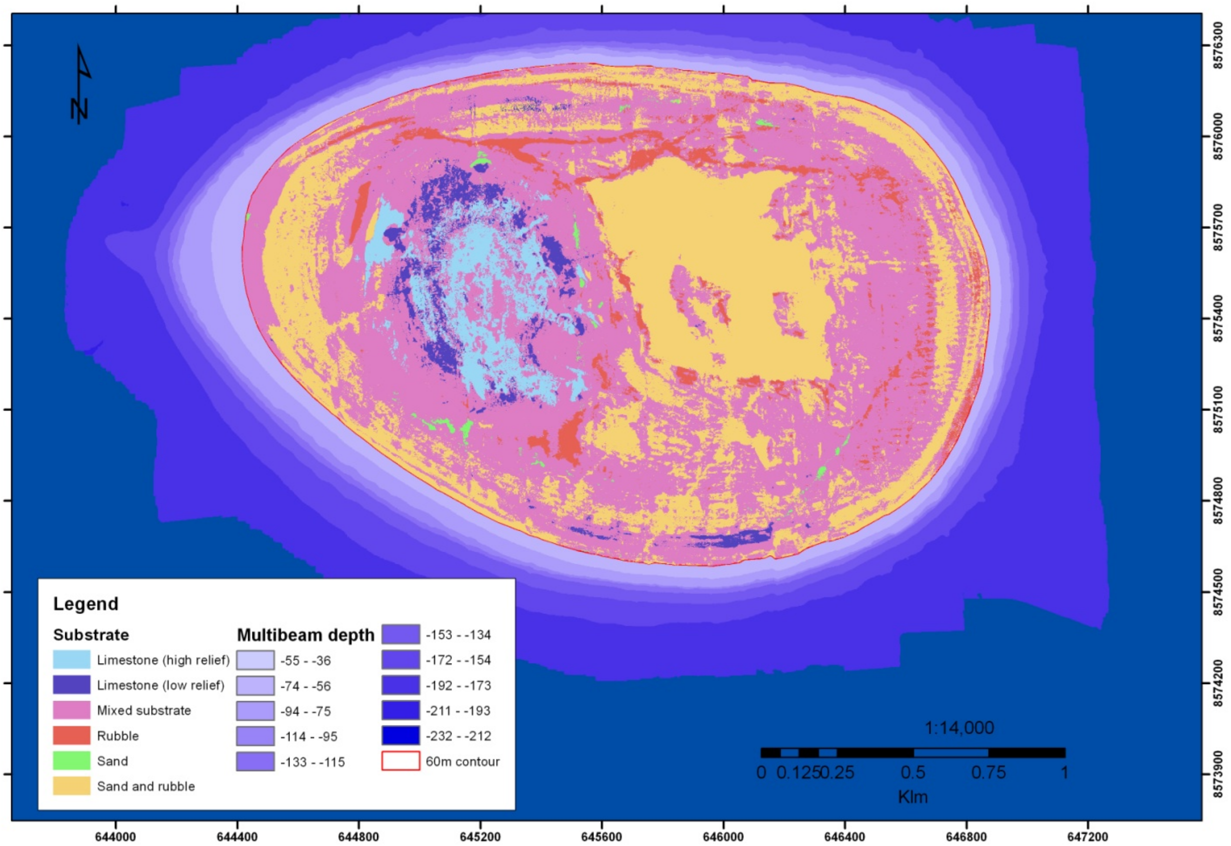


Figure 3.30. Composite substrate habitat map Goeree Shoal.

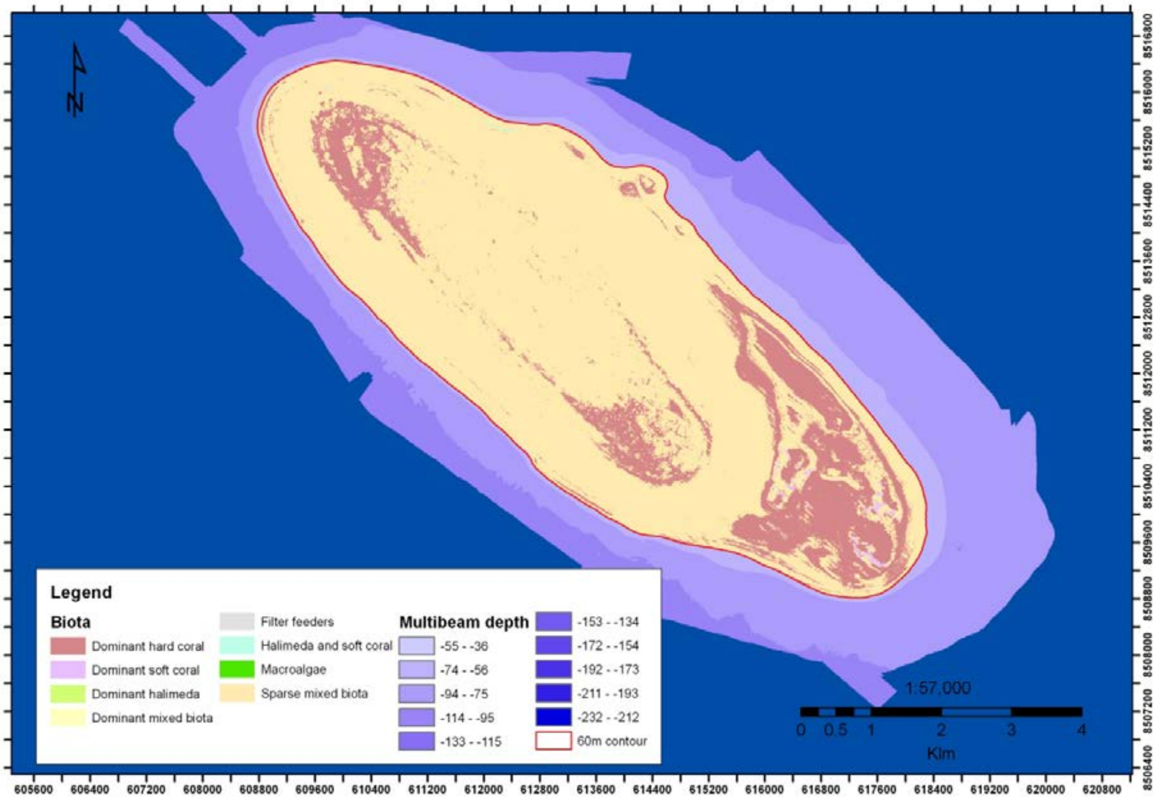


Figure 3.31. Composite biotic habitat map Heywood Shoal.

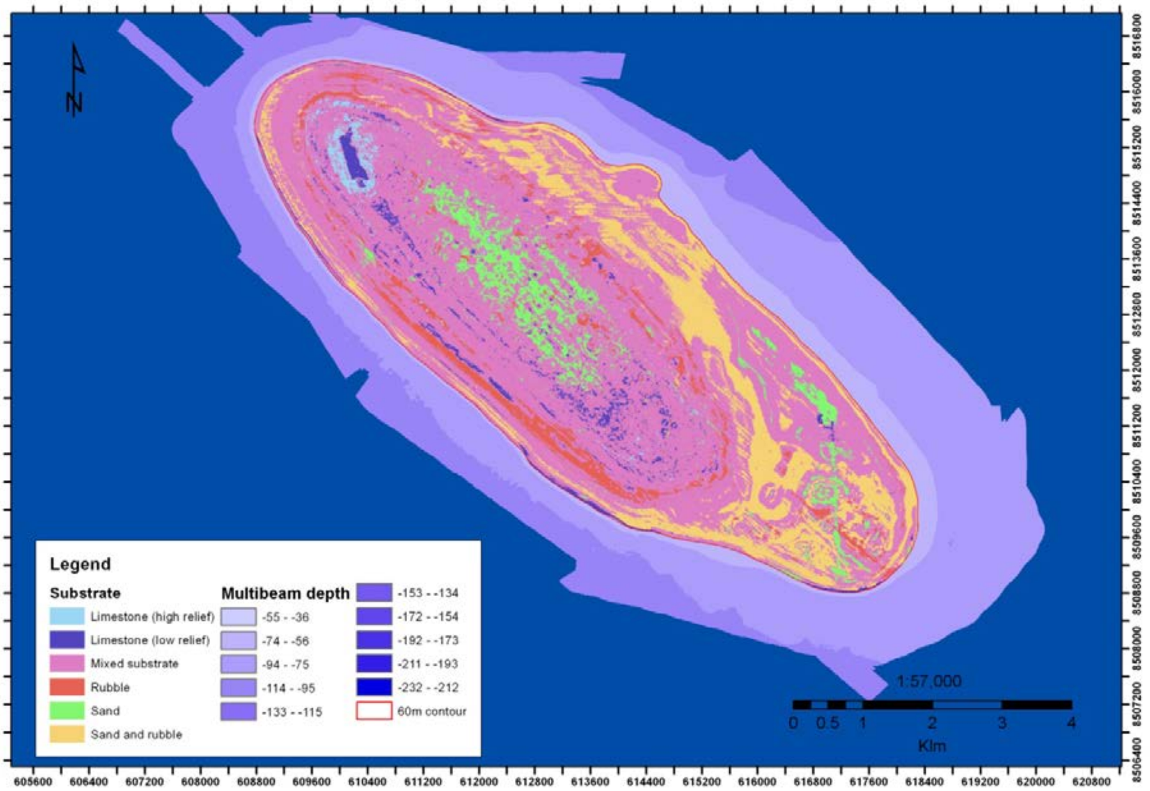


Figure 3.32. Composite substrate habitat map Heywood Shoal.

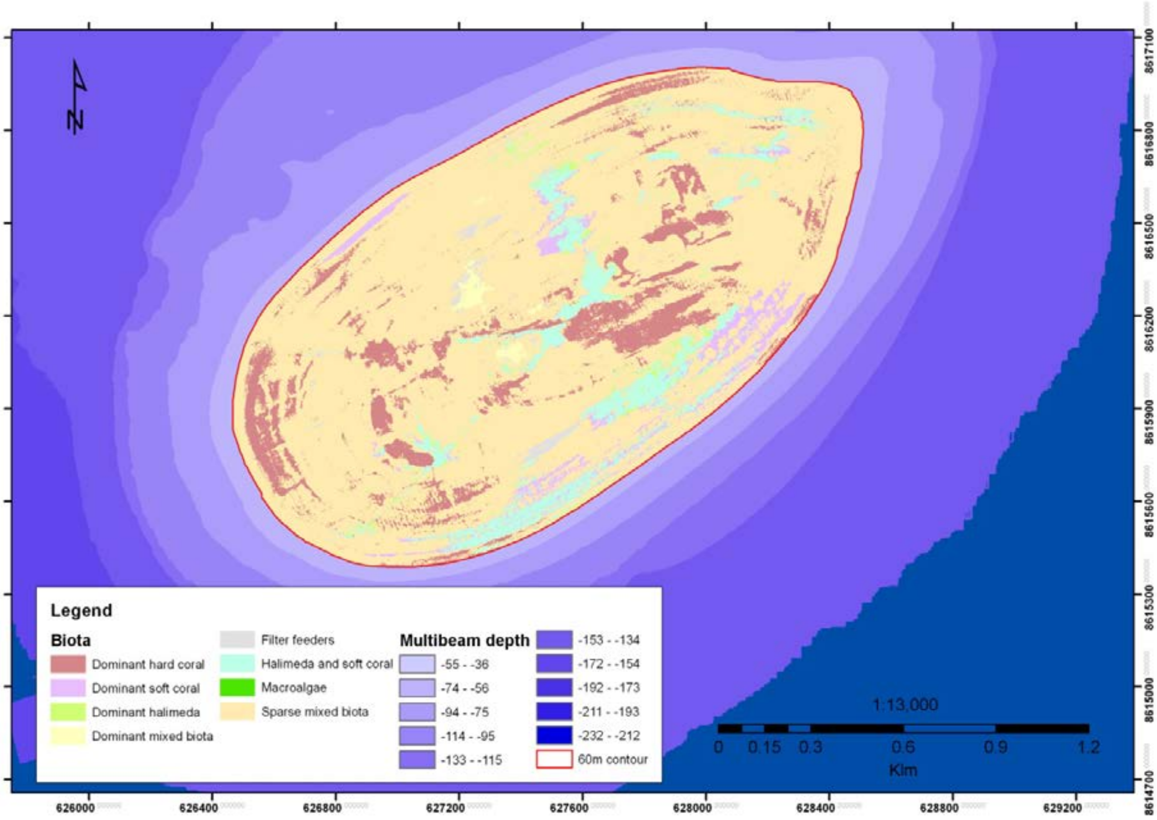


Figure 3.33. Composite biotic habitat map Shoal 25.

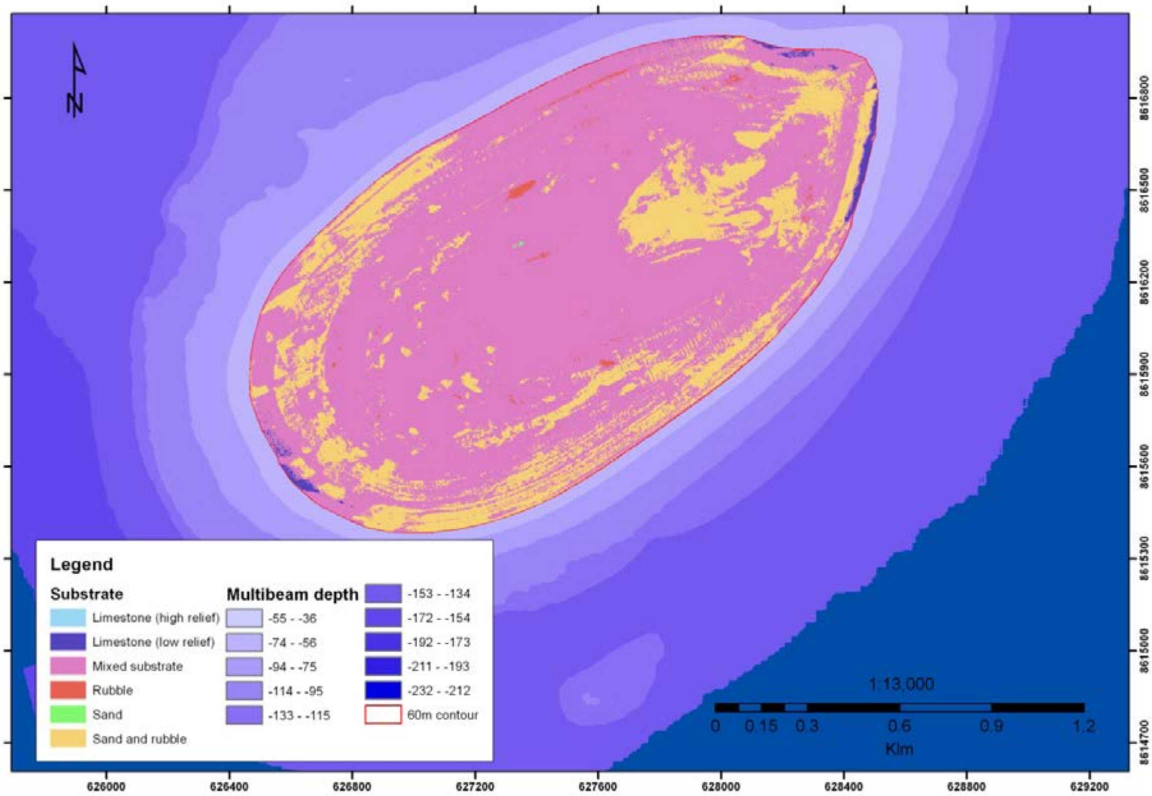


Figure 3.34. Composite substrate map Shoal 25.

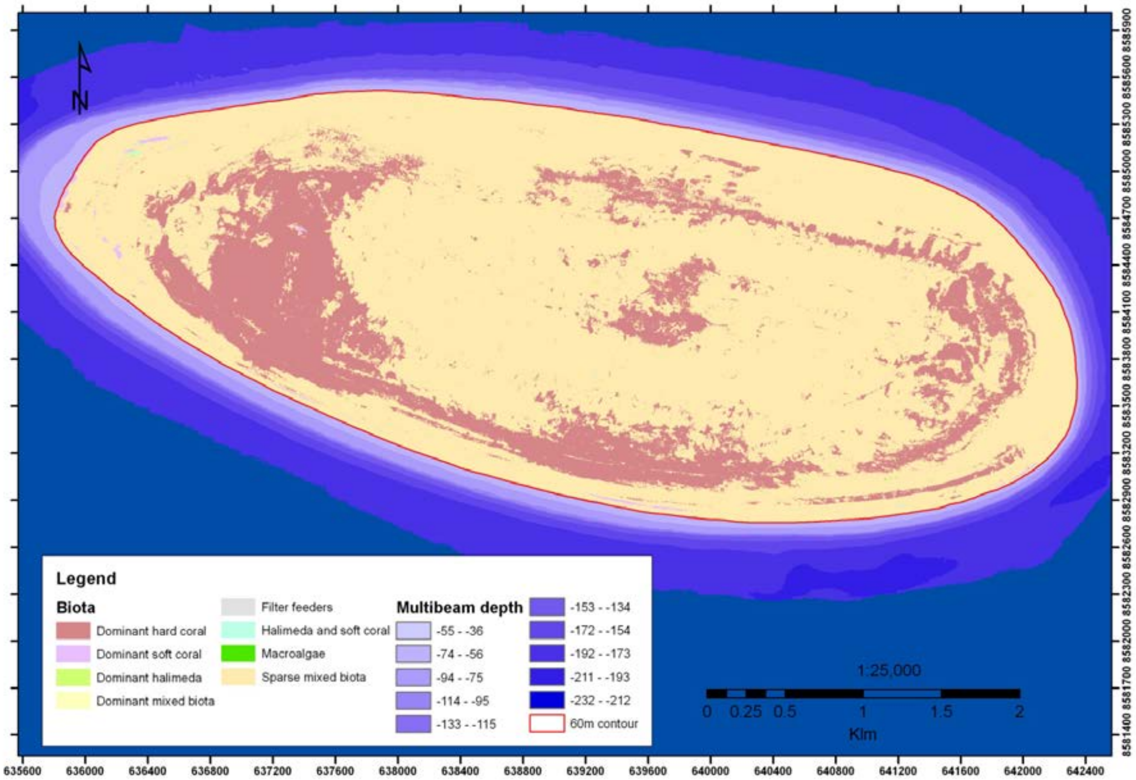


Figure 3.35. Composite biotic habitat maps Vulcan Shoal.

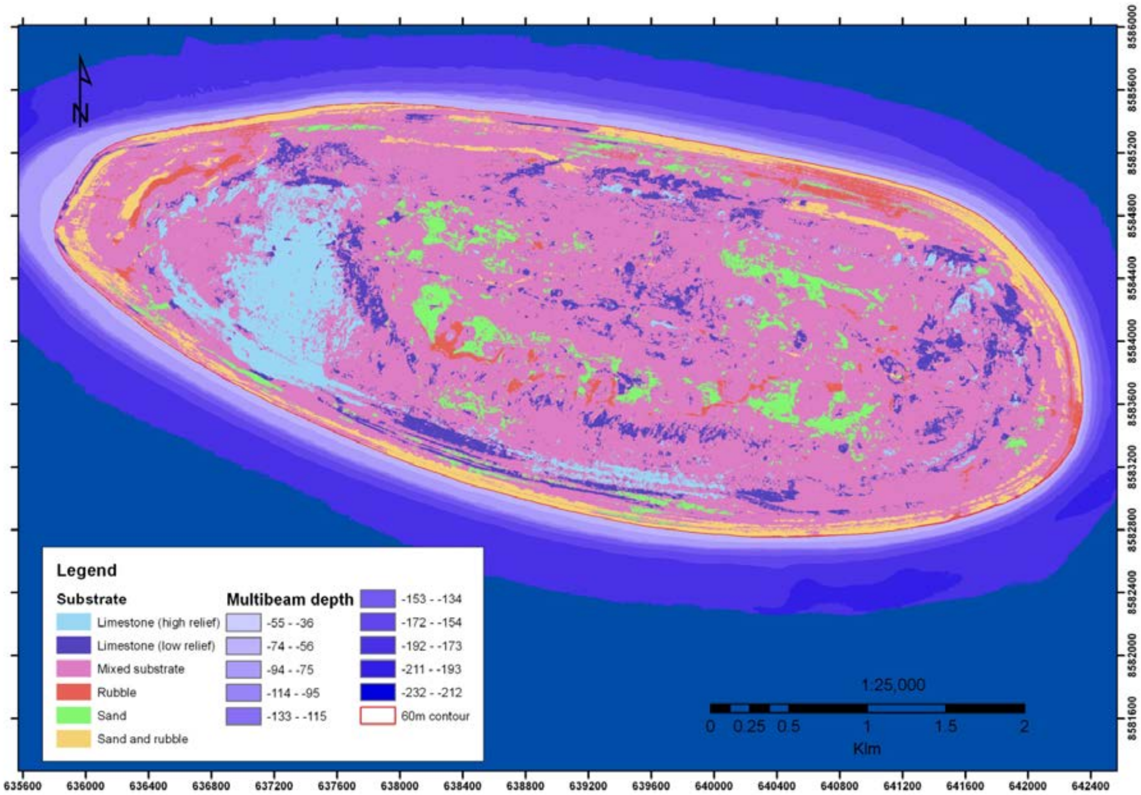


Figure 3.36. Composite substrate habitat map Vulcan Shoal.

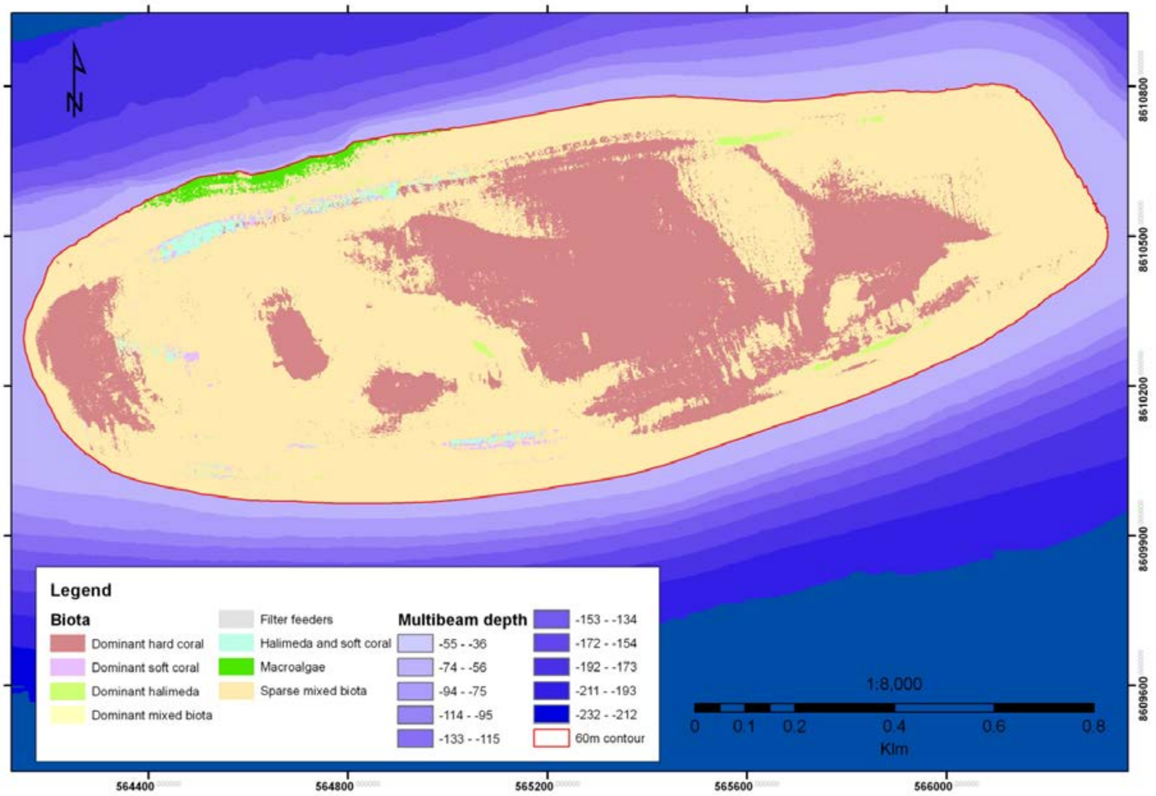


Figure 3.37. Composite biota habitat map Wave Governor Bank.

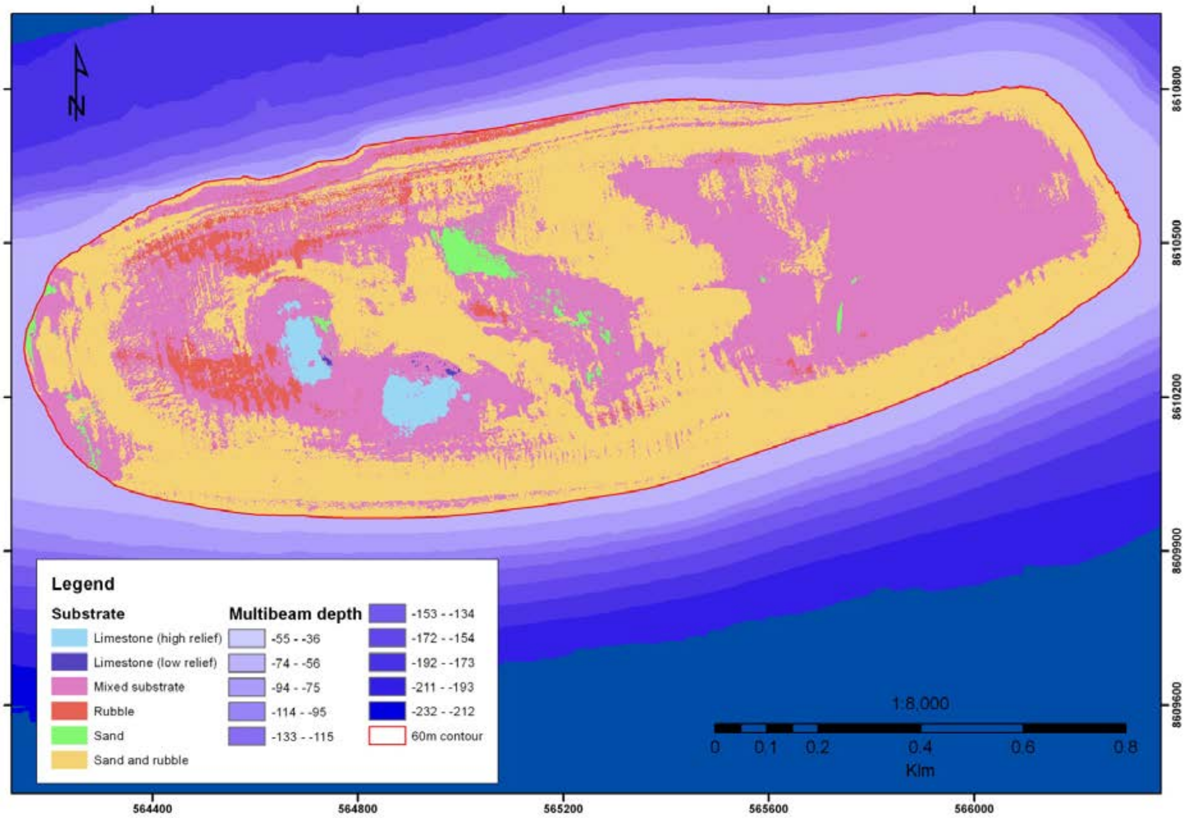


Figure 3.38. Composite substrate habitat map Wave Governors Bank.

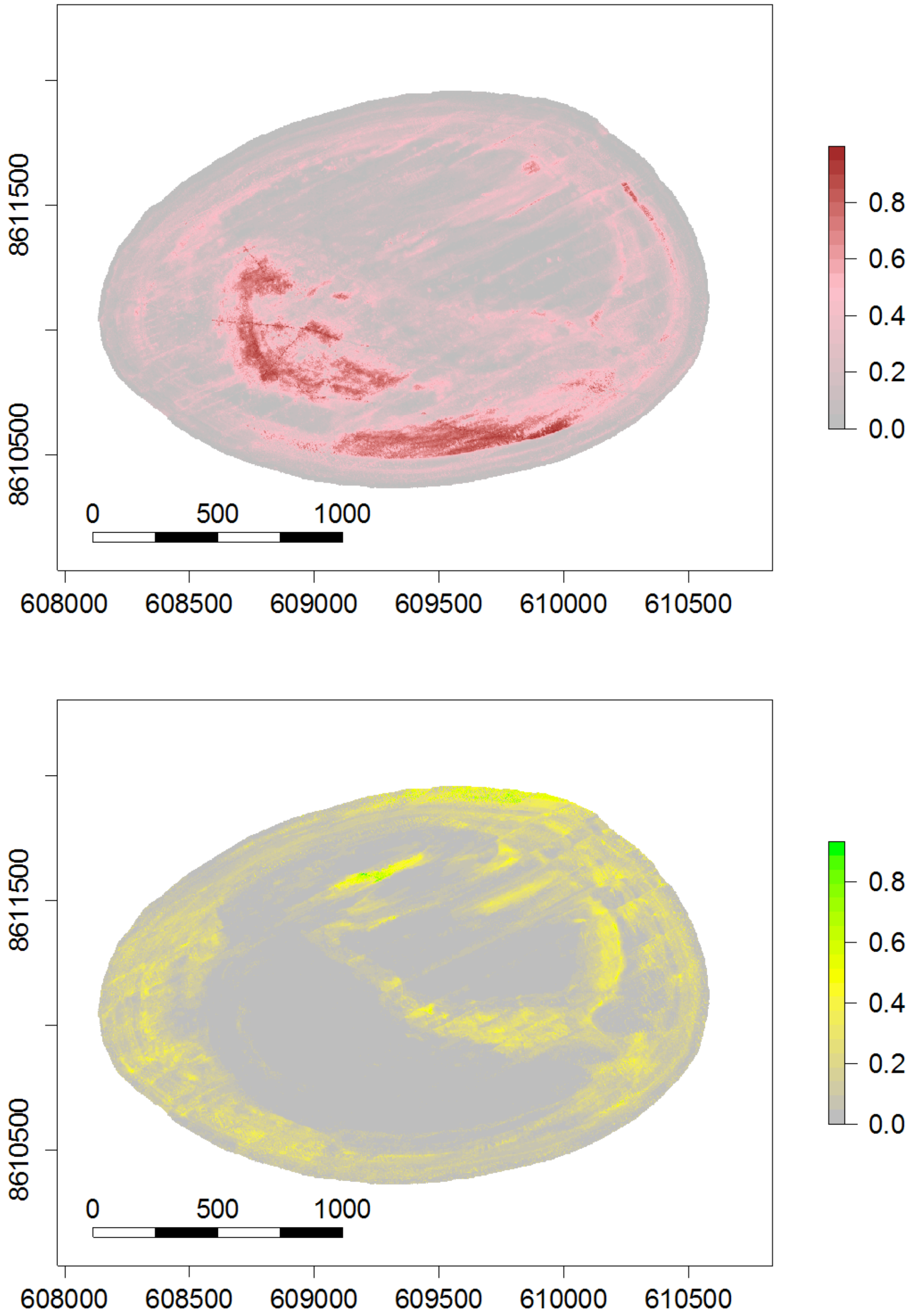


Figure 3.39. Barracouta West: probability of occurrence of sensitive habitats; hard coral (top) and *Halimeda* (bottom).

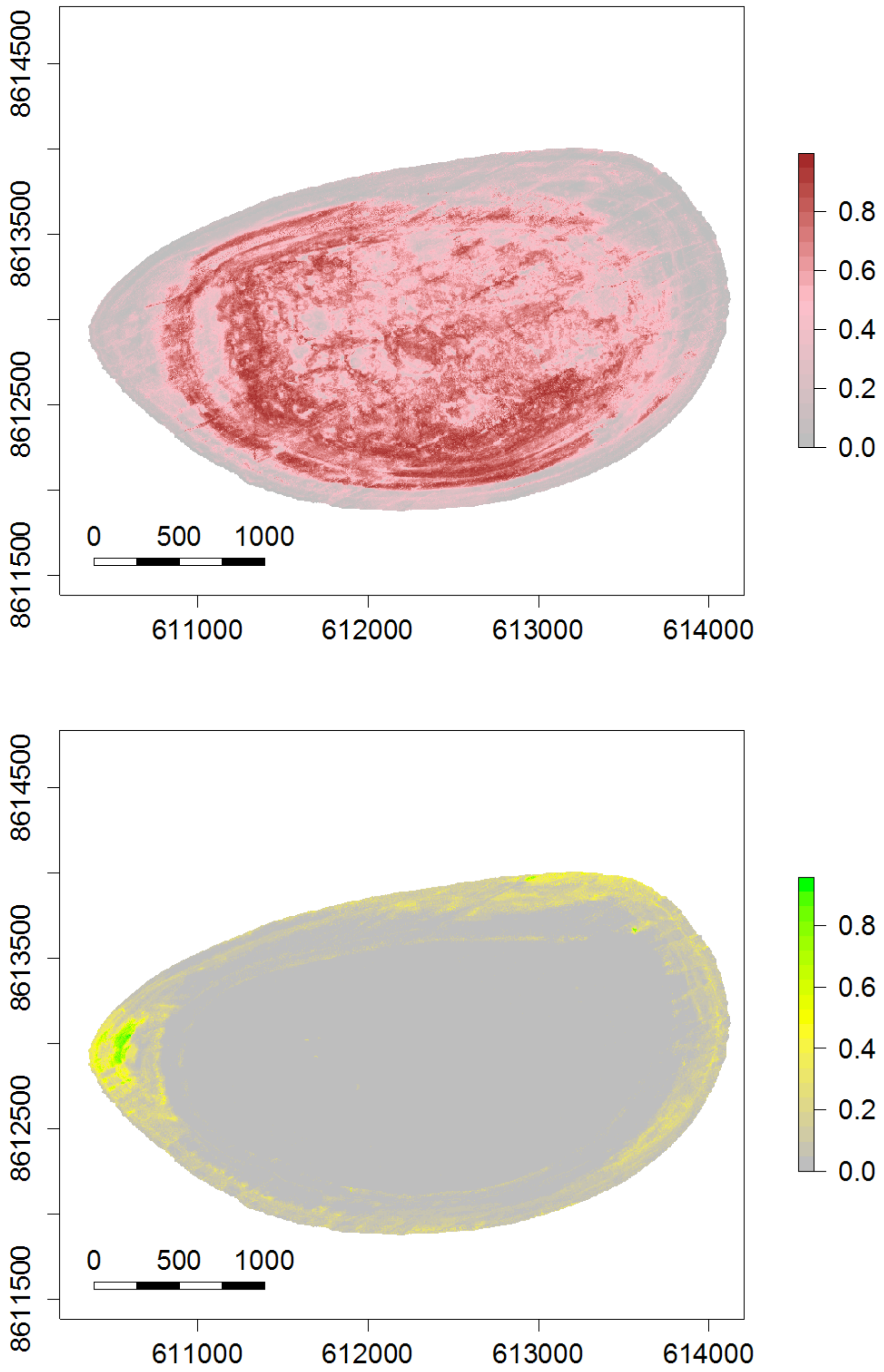


Figure 3.40. Barracouta East: probability of occurrence of sensitive habitats; hard coral (top) and *Halimeda* (bottom).

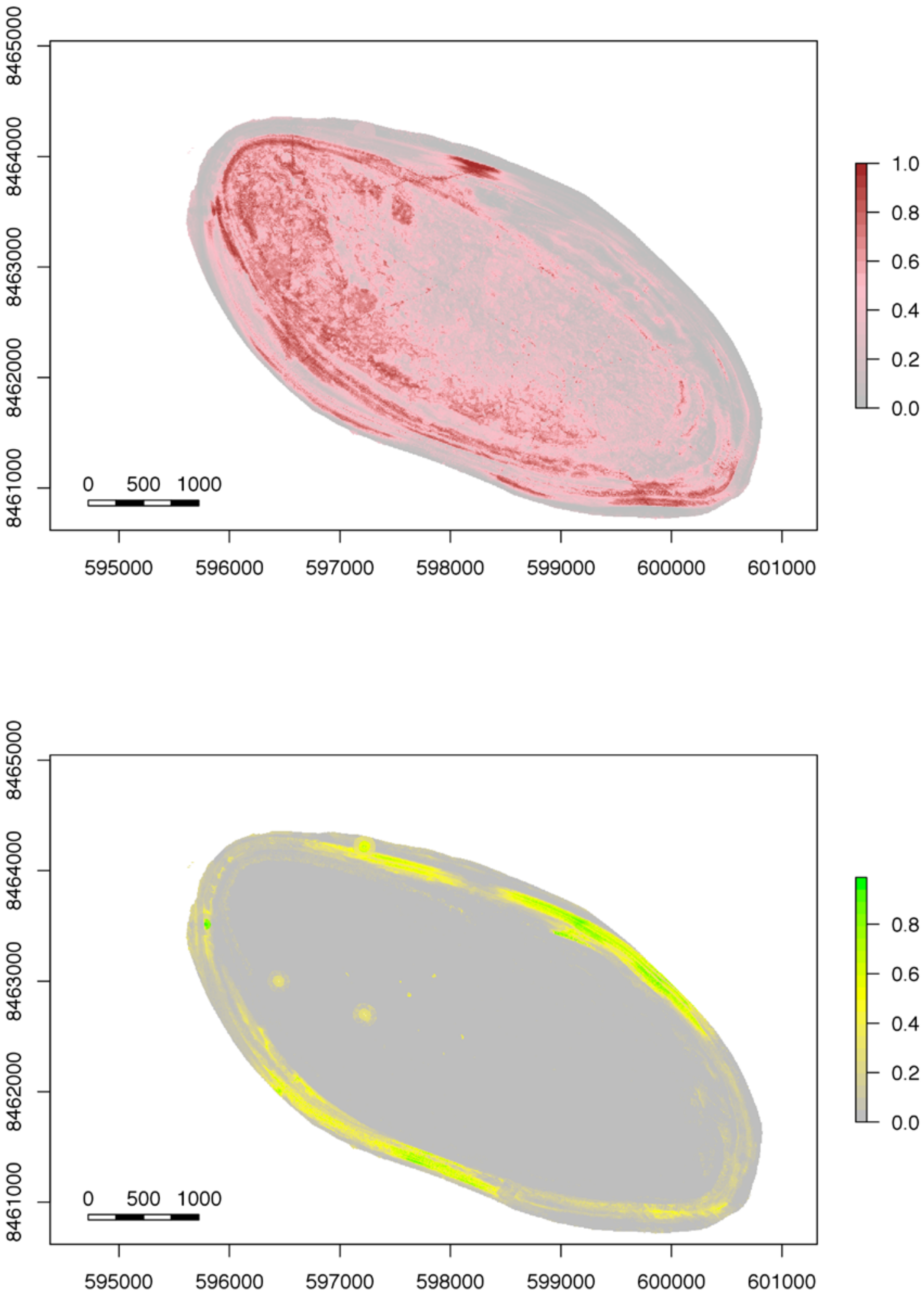


Figure 3.41. Euchuca shoal: probability of occurrence of sensitive habitat; hard coral (top) and halimeada (bottom).

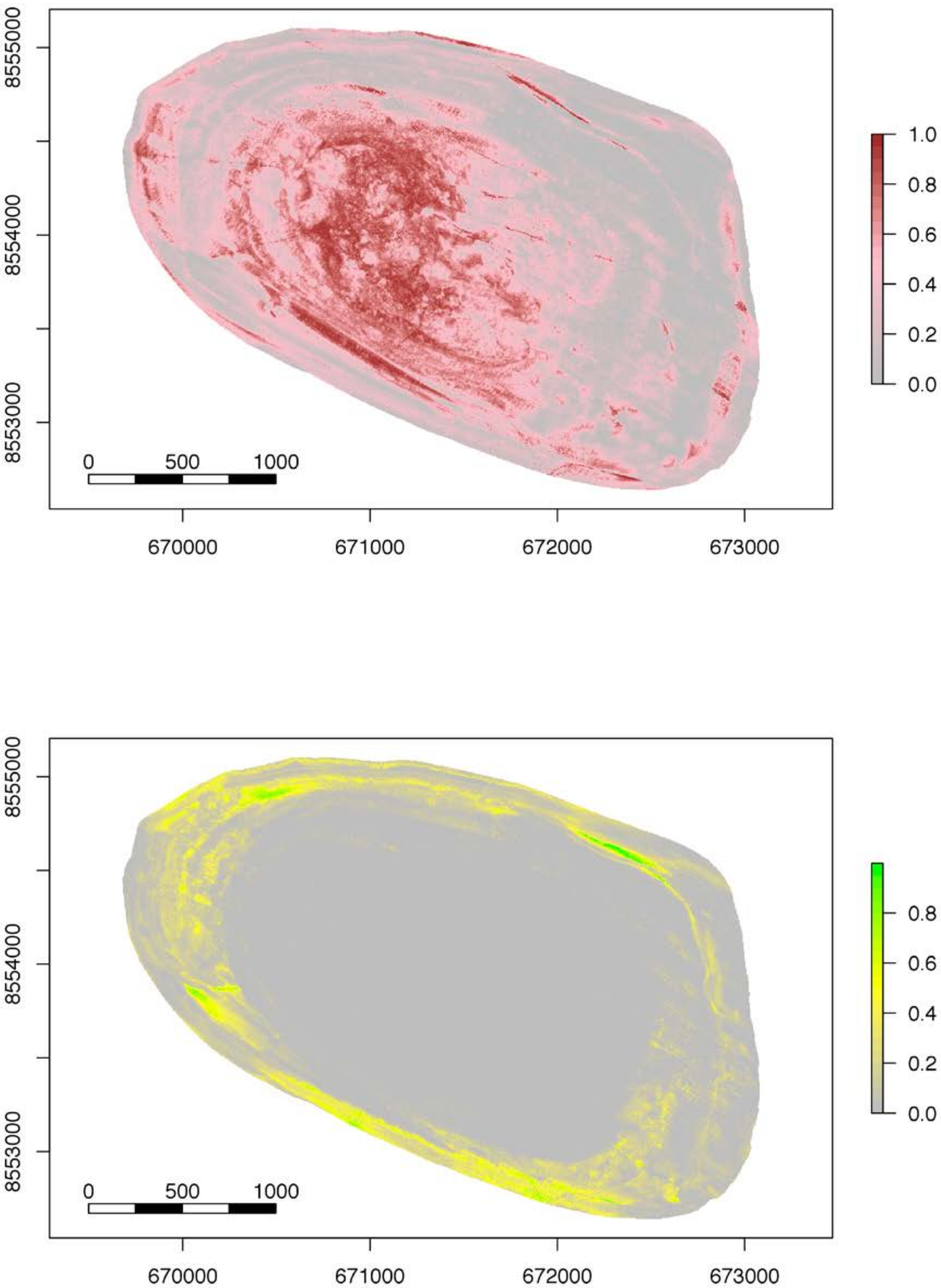
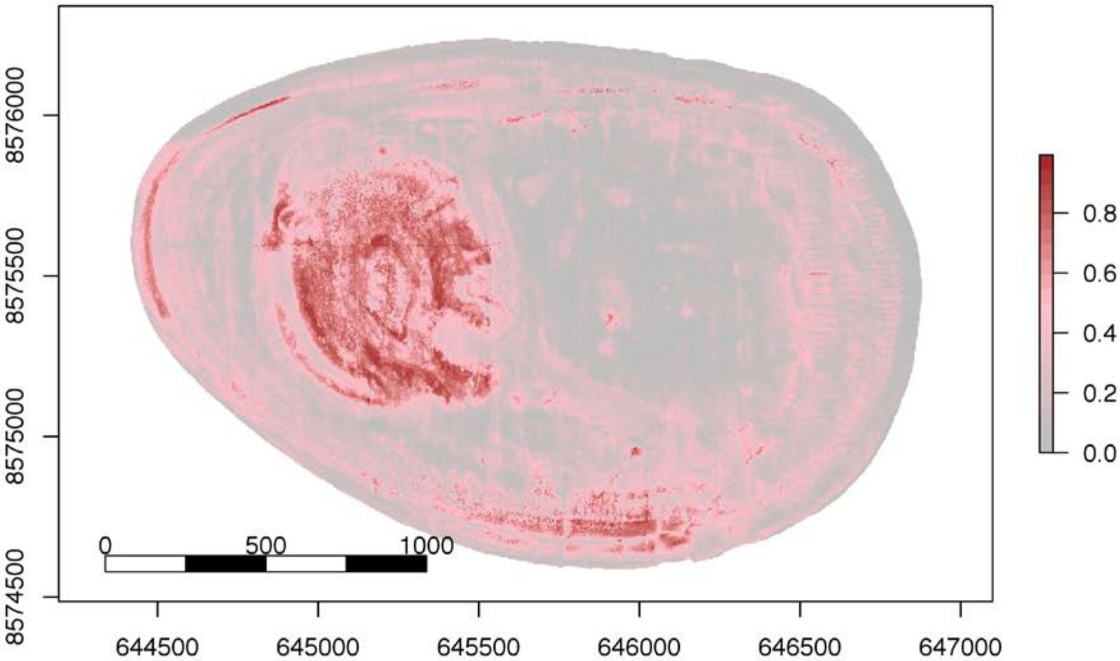


Figure 3.42. Eugene McDermott: probability of occurrence of sensitive habitats; hard coral (top) and *Halimeda* (bottom).



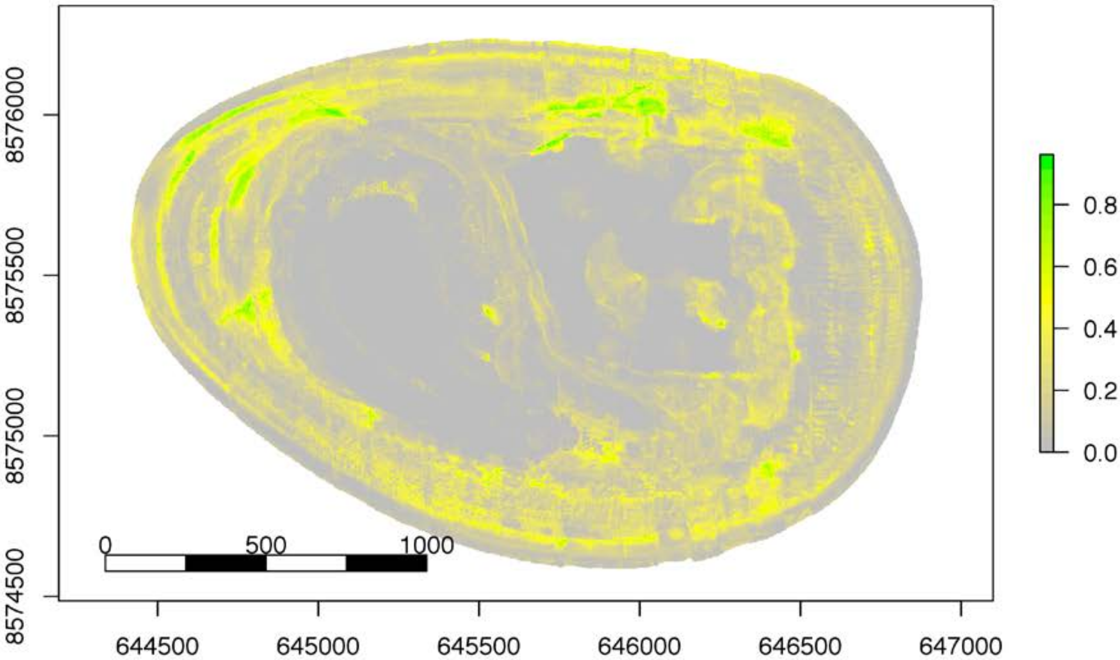
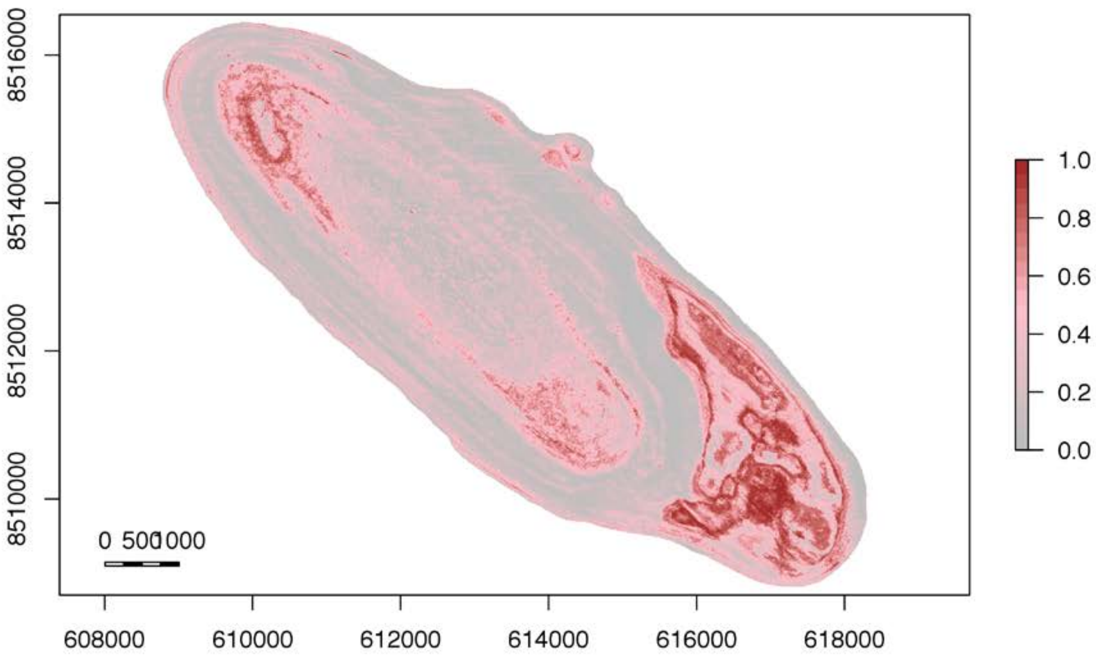


Figure 3.43. Goeree shoal: probability of occurrence of sensitive habitats; hard coral (top) and *Halimeda* (bottom).



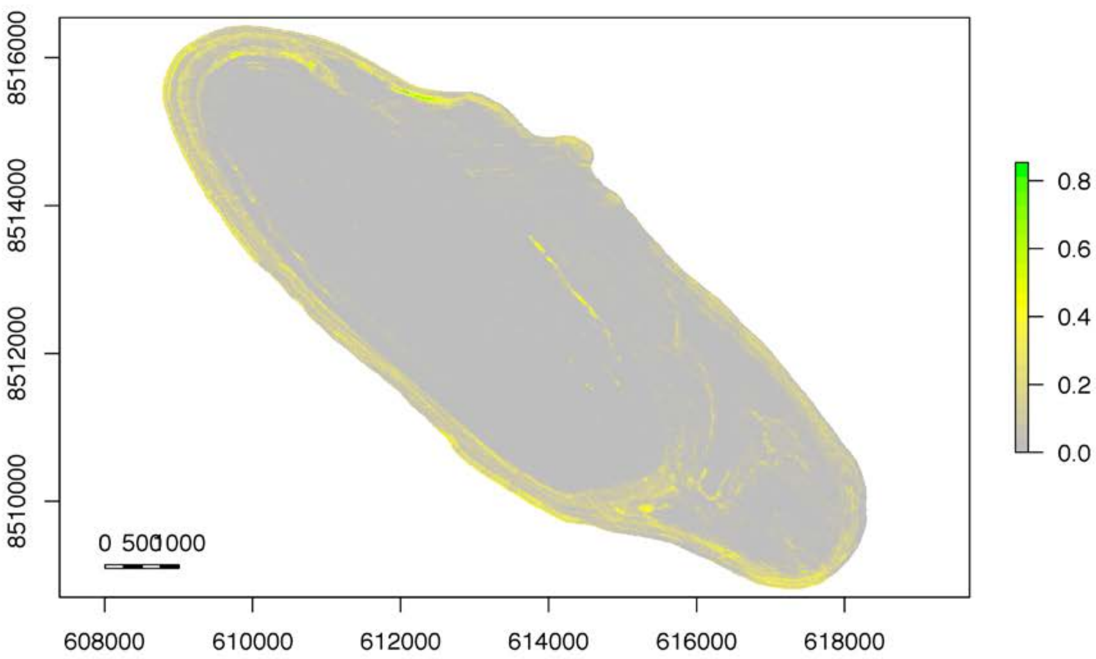


Figure 3.44. Heywood shoal: probability of occurrence of sensitive habitats; hard coral (top) and halimeada (bottom).

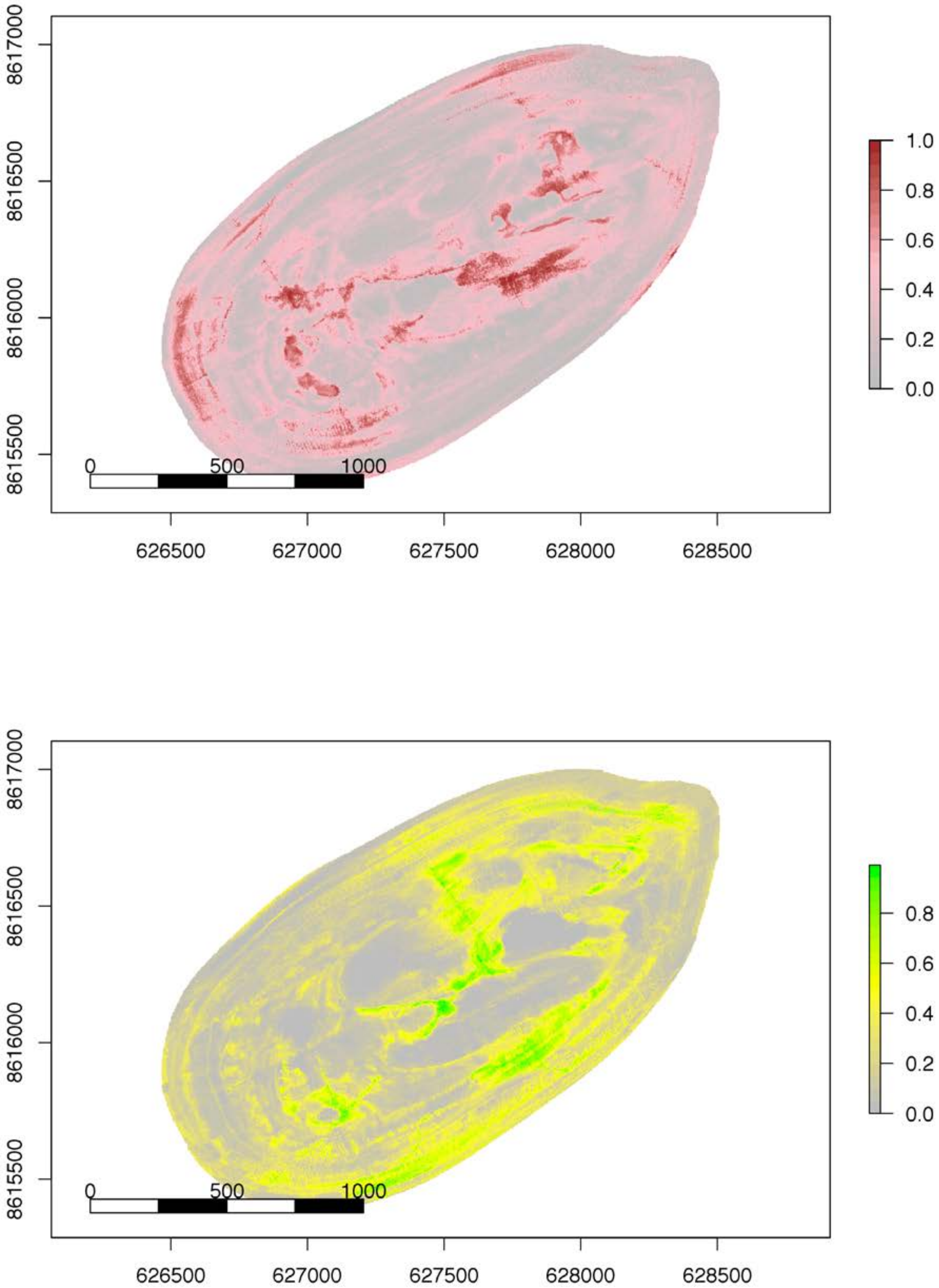
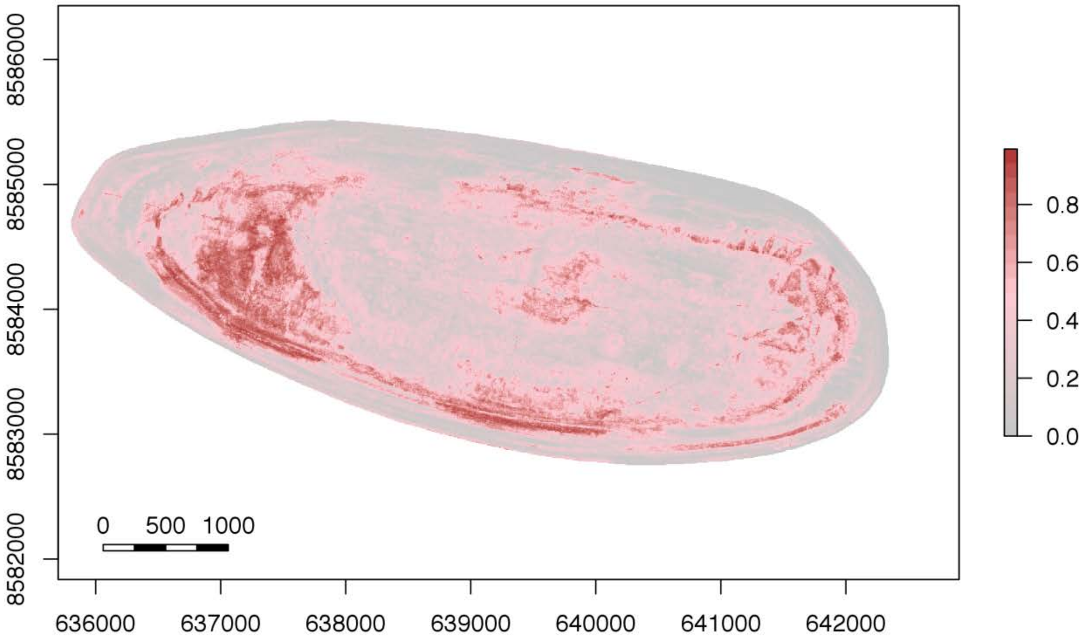


Figure 3.45. Shoal 25: probability of occurrence of sensitive habitats; hard coral (top) and *Halimeda* (bottom)



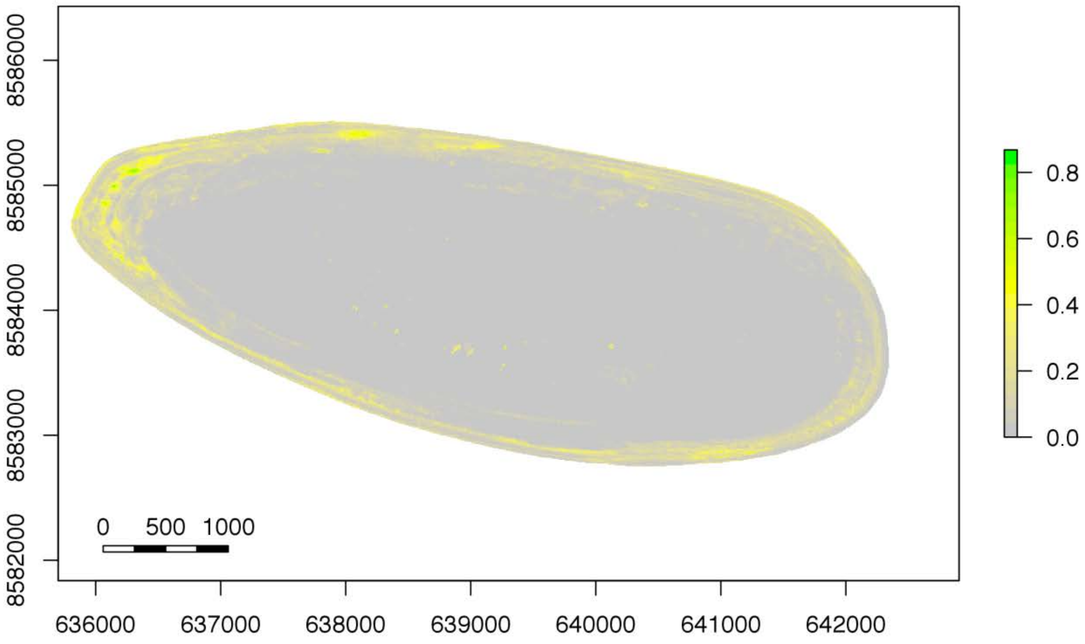
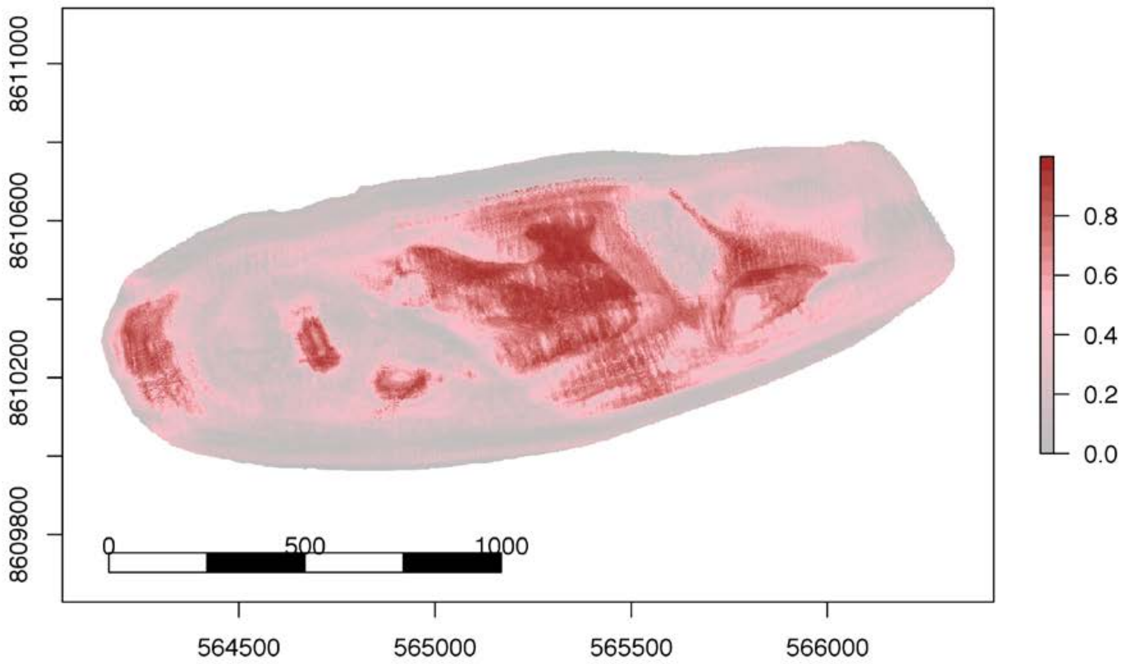


Figure 3.46. Vulcan shoal: probability of occurrence of sensitive habitats; hard coral (top) and *Halimeda* (bottom).



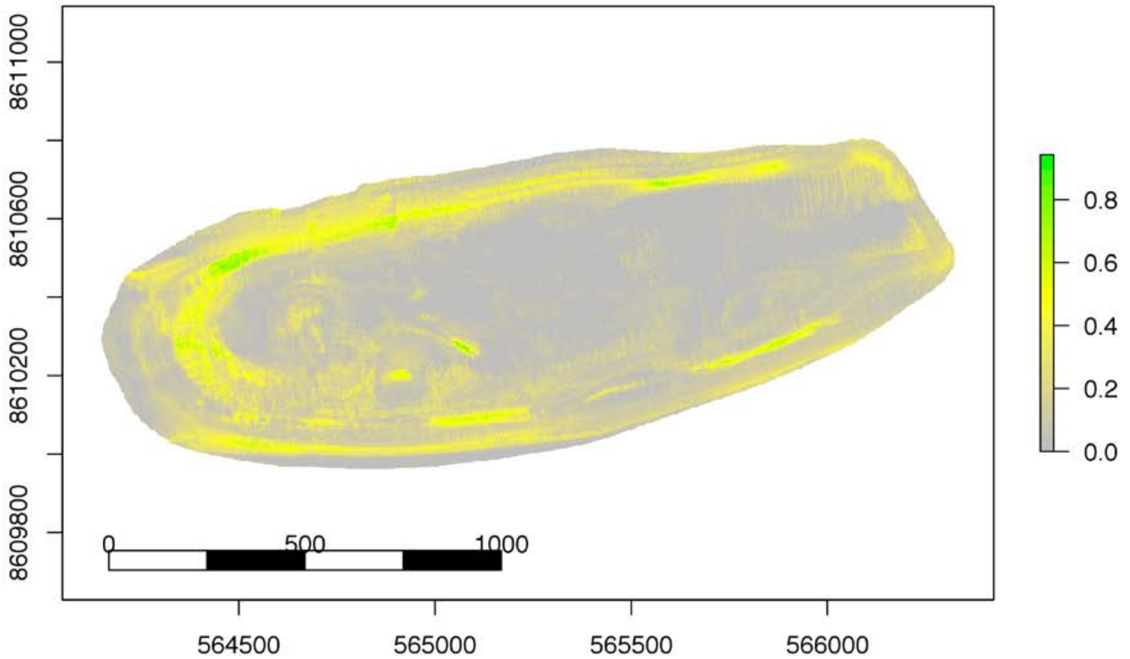


Figure 3.47. Wave Governor bank: probability of occurrence sensitive habitats; hard coral (top) and *Halimeda* (bottom).

3.4.3 Gradient analysis results

Neither the physical variables nor the three oil exposure variables explained significant variability in benthic composition across the nine shoals (R^2 values <1, Tables 3.5 to 3.10). While model fits were generally weak, they do allow a relative ranking of the importance of the included physical variables in structuring benthic communities, and any potential affect of the Montara uncontrolled release.

Models containing slope and/or aspect were the best for predicting total algal cover across the nine shoals. Although the best model was a single variable model containing only slope, a large number of models were within 2 AIC of this and thus should be considered equally valid (Table 3.5). The influence of the oil spill variables was ambiguous, with distance from the uncontrolled release being included in the third best model (with slope, Table 3.5) and not significantly different to the single variable model with slope (p=0.27). At a finer taxonomic scale, coralline algae were best predicted by depth, although again several models were within 2 AIC of the best model (including only depth, Table 3.6). While the second best model did contain minimum hours of oil exposure, this was not significantly different to a model with only depth (p=0.18).

Unlike algae a single best model was identified for total hard coral cover, which included depth, aspect and rugosity (Table 3.7). Of the three oil exposure variables, presence of oil produced the second best model, which was not significantly different to a model excluding this variable (p=0.19). Presence of oil was also the best oil exposure variable for coral data examined at the family level (Table 3.8). For the Acroporidae, the best model was a single variable model containing depth, followed by a model including both depth and oil exposure (Table 3.8A), which were not significantly different (p=0.18). Pocilloporidae showed one of the strongest responses to the presence of oil, with this variable being included in the best model (Table 3.8B), although still not significantly better at the alpha = 0.05 level than the best competing model including only physical variables (p=0.10). For the index of community structure of hard corals, a model including the presence of oil ranked third (Table 3.8C) and was not significantly different to the best model containing only physical variables (p=0.33).

Models containing aspect and rugosity were consistently included among the best set for sponges (Table 3.9). The best model including an oil exposure variable was ranked third and the presence of oil (Table 3.9) and was not significantly different from that containing only the physical variables (p=0.46).

The ascidian was the only other variable examined (besides Pocilloporidae) where the best model included an oil exposure variable (presence of oil, Table 3.10), although again this model was not significantly different from one where it was excluded (p=0.14).

Table 3.5. GAMM mixed modeling results for the major benthic category Algae. Three exposure variables (Dist - distance from spill; Exp - minimum hours of exposure; and Pres – Presence or absence of oil at the site, see columns highlighted in green) were added to all best models (within 2 AIC of that with the lowest AIC) from a complete subsets analysis of six physical variables (mean depth of the transect – Depth; a measure of north-south aspect – Asp; slope – Slope ; rugosity - Rug, longitude – Lon; and latitude - Lat). Models are sorted so that the best model (as determined by AIC) is at the top, with all models within 2 AIC highlighted in yellow.

Dist	Exp	Pres	Depth	Asp	Slope	Rug	Lon	Lat	R^2	AIC	AICw
					y				0.01	3452.64	0.09
				y					0.02	3452.95	0.08
y				y					0.06	3453.41	0.06
y					y				0.05	3453.42	0.06
				y	y				0.02	3453.59	0.06
			y	y					0.01	3454.04	0.04
y				y	y				0.1	3454.16	0.04
		y			y				0.02	3454.25	0.04
			y						0	3454.26	0.04
						y			0.01	3454.31	0.04
				y			Y		0.03	3454.31	0.04
		y		y					0.02	3454.56	0.03
				y		y			0.02	3454.59	0.03
y			y	y					0.05	3454.9	0.03
	y			y					0.02	3454.95	0.03
y				y		y			0.06	3455.2	0.02
y				y			y		0.06	3455.41	0.02
y						y			0.04	3455.44	0.02
y			y						0.03	3455.53	0.02
		y	y	y					0.01	3455.71	0.02
	y				y				0.04	3455.75	0.02
		y				y			0.01	3455.94	0.02
		y	y						0	3455.98	0.02
	y		y	y					0.01	3456.04	0.02
		y		y			y		0.04	3456.13	0.02
		y		y		y			0.02	3456.18	0.02
		y		y	y				0.05	3456.19	0.02
	y		y						0	3456.26	0.01
	y					y			0.01	3456.31	0.01
	y			y			y		0.03	3456.31	0.01
	y			y		y			0.02	3456.59	0.01
	y			y	y				0.05	3456.75	0.01

Table 3.6. GAMM mixed modeling results for coralline algae. Three exposure variables (Dist - distance from uncontrolled release; Exp - minimum hours of exposure; and Pres – Presence of absence of oil at the site, see columns highlighted in green) were added to all best models (within 2 AIC of that with the lowest AIC) from a complete subsets analysis of six physical variables (mean depth of the transect – Depth; a measure of north-south aspect – Asp; slope – Slope ; rugosity - Rug, longitude – Lon; and latitude - Lat). Models are sorted so that the best model (as determined by AIC) is at the top, with all models within 2 AIC highlighted in yellow.

Dist	Exp	Pres	Depth	Asp	Slope	Rug	Lon	Lat	R^2	AIC	AICw
			y						0.14	1458.14	0.22
	y		y						0.15	1458.31	0.2
			y		y				0.14	1458.74	0.17
	y		y		y				0.15	1459.37	0.12
		y	y		y				0.14	1459.92	0.09
y			y						0.14	1460.14	0.08
y			y		y				0.14	1460.74	0.06
		y	y						0.14	1461.05	0.05

Table 3.7. GAMM mixed modeling results for the major benthic category Hard Coral. Three exposure variables (Dist - distance from spill; Exp - minimum hours of exposure; and Pres – Presence of absence of oil at the site, see columns highlighted in green) were added to all best models (within 2 AIC of that with the lowest AIC) from a complete subsets analysis of six physical variables (mean depth of the transect – Depth; a measure of north-south aspect – Asp; slope – Slope ; rugosity - Rug, longitude – Lon; and latitude - Lat). Models are sorted so that the best model (as determined by AIC) is at the top, with all models within 2 AIC highlighted in yellow.

Dist	Exp	Pres	Depth	Asp	Slope	Rug	Lon	Lat	R^2	AIC	AICw
			y	y		y			0.21	452.74	0.39
		y	y	y		y			0.24	453.04	0.33
y			y	y		y			0.21	454.74	0.14
	y		y	y		y			0.21	454.74	0.14

Table 3.8. GAMM mixed modeling results for family level data for hard corals, including: Acroporidae (A), Pocilloporidae (B) and an index of community structure (C). Three exposure variables (Dist - distance from uncontrolled release; Exp - minimum hours of exposure; and Pres – Presence or absence of oil at the site, see columns highlighted in green) were added to all best models (within 2 AIC of that with the lowest AIC) from a complete subsets analysis of six physical variables (mean depth of the transect – Depth; a measure of north-south aspect – Asp; slope – Slope ; rugosity over a 100 m scale - Rug, longitude – Lon; and latitude - Lat). Models are sorted so that the best model (as determined by AIC) is at the top, with all models within 2 AIC highlighted in yellow.

(A) Acroporidae

Dist	Exp	Pres	Depth	Asp	Slope	Rug	Lon	Lat	R^2	AIC	AICw
			y						0.25	251.93	0.16
		y	y						0.31	252.12	0.14
			y	y					0.26	252.69	0.11
		y	y	y					0.31	252.8	0.1
			y		y				0.25	253.92	0.06
			y			y			0.25	253.92	0.06
y			y						0.25	253.93	0.06
	y		y						0.25	253.93	0.06
		y	y		y				0.31	254.12	0.05
		y	y			y			0.31	254.12	0.05
y			y	y					0.28	254.6	0.04
	y		y	y					0.26	254.69	0.04
	y		y		y				0.25	255.7	0.02
	y		y			y			0.25	255.86	0.02
y			y		y				0.25	255.92	0.02
y			y			y			0.25	255.93	0.02

(B) Pocilloporidae

Dist	Exp	Pres	Depth	Asp	Slope	Rug	Lon	Lat	R^2	AIC	AICw
		y		y					0.05	-0.35	0.25
				y					0.02	0.3	0.18
		y	y	y					0.05	1.65	0.09
		y		y			y		0.05	1.65	0.09
				y			y		0.03	1.91	0.08
	y			y					0.02	2.3	0.07
			y	y					0.02	2.3	0.07
y				y					0.02	2.3	0.07
	y			y			y		0.03	3.91	0.03
y				y			y		0.03	3.91	0.03
	y		y	y					0.02	4.3	0.02
y			y	y					0.02	4.3	0.02

(C) Coral community structure

Dist	Exp	Pres	Depth	Asp	Slope	Rug	Lon	Lat	R^2	AIC	AICw
			y		y				0.41	-291.81	0.28
			y			y			0.41	-291.05	0.19
		y	y		y				0.44	-290.76	0.17
y			y		y				0.41	-289.81	0.1
	y		y		y				0.41	-289.81	0.1
	y		y			y			0.41	-289.05	0.07
y			y			y			0.41	-289.05	0.07
		y	y			y			0.43	-269.22	0

Table 3.9. GAMM mixed modeling results for the major benthic category Sponges. Three exposure variables (Dist - distance from uncontrolled release; Exp - minimum hours of exposure; and Pres – Presence of absence of oil at the site, see columns highlighted in green) were added to all best models (within 2 AIC of that with the lowest AIC) from a complete subsets analysis of six physical variables (mean depth of the transect – Depth; a measure of north-south aspect – Asp; slope – Slope ; rugosity - Rug, longitude – Lon; and latitude - Lat). Models are sorted so that the best model (as determined by AIC) is at the top, with all models within 2 AIC highlighted in yellow.

Dist	Exp	Pres	Depth	Asp	Slope	Rug	Lon	Lat	R^2	AIC	AICw
				y		y			0.05	288.87	0.23
				y		y		y	0.08	290.05	0.12
		y		y		y			0.05	290.33	0.11
		y		y		y		y	0.1	290.62	0.09
			y	y		y			0.05	290.81	0.09
y				y		y			0.05	290.87	0.08
	y			y		y			0.05	290.87	0.08
	y			y		y		y	0.08	292.05	0.05
y				y		y		y	0.08	292.05	0.05
		y	y	y		y			0.06	292.26	0.04
	y		y	y		y			0.05	292.81	0.03
y			y	y		y			0.05	292.81	0.03

Table 3.10. GAMM mixed modeling results for the Ascidian. Three exposure variables (Dist - distance from uncontrolled release; Exp - minimum hours of exposure; and Pres – Presence of absence of oil at the site, see columns highlighted in green) were added to all best models (within 2 AIC of that with the lowest AIC) from a complete subsets analysis of six physical variables (mean depth of the transect – Depth; a measure of North-South aspect – Asp; slope – Slope ; rugosity - Rug, longitude – Lon; and Latitude - Lat). Models are sorted so that the best model (as determined by AIC) is at the top, with all models within 2 AIC highlighted in yellow.

Dist	Exp	Pres	Depth	Asp	Slope	Rug	Lon	Lat	R^2	AIC	AICw
		y	y	y		y			0.2	825.97	0.43
			y	y		y			0.07	826.12	0.4
	y		y	y		y			0.07	828.12	0.15
y			y	y		y			0.06	832.8	0.01

3.5 Conclusions

All shoals in this survey exhibited a benthic community on their plateau regions dominated by photosynthetic organisms. The major types of organisms, algae, hard corals, sponges and soft corals, were consistently present, but varied in their relative importance, spatial distributions and exact species compositions. Algal turfs and crustose coralline algae were the most abundant plants. There was a clear correlation between depth and live coral cover, with the most diverse and abundant coral found typically on the shallowest areas of each shoal. The coral assemblages varied between shoals, but broadly grouped into shallower shoals with corals in the families Acroporidae and Poritidae dominant, while deeper shoal margins, particularly at Heywood Shoal, and the two deepest shoals, Wave Governor Bank and Shoal 25, were strongly characterised by an abundance of various mushroom coral species in the family Fungiidae. The benthic biota is typical of shallow tropical reef systems studied elsewhere, with many coral and algal species shared between the shoals and also emergent coral reefs in this region. The shoal benthic communities may therefore act as stepping stones for enhanced biological connectivity throughout both the submerged and emergent reef systems of Australia's northwest.

The range of live hard coral cover varied from 6.1-17.7%, which would be regarded as low to moderate for transects placed on a shallow reef in a potentially coral-dominate habitat. However, as these shoal surveys integrated data across the entire shoal plateau, the live coral cover present may be comparable to, or higher than, that found on some shallow reefs, if the sampling were to include lagoonal sandy habitats. For example, a recent hyperspectral habitat survey of the entire Ningaloo Reef Marine Park, which assessed live coral cover across the lagoonal and reef crest habitats, found the overall mean coral cover to be 7% (H. Kobryn, pers.comm. A. Heyward). Consequently, the coral cover on the shoals seems notable and can be high within particular habitats.

There was no obvious sign of widespread stress, such as bleached or recently dead corals, in the sessile benthos, but without baseline data from before the uncontrolled release, temporal changes remain unknown. The two shoals, Vulcan and Barracouta, surveyed in both 2010 and 2011 provide evidence of a major change in the benthic community at Vulcan, yet little inter-annual change at Barracouta. The extensive seagrass meadows found across Vulcan Shoal in 2010 have almost completely disappeared, with almost all leaf material absent in the 2011 survey. Only extensive remnant rhizomes remain, indicating where the seagrass was, although there was evidence of a few new leaf shoots developing from the remnant rhizomes. The appearance of Vulcan Shoals coral was normal and had not decreased, supporting the possibility that the cause of the seagrass loss was either selective to seagrass, or physical in nature affecting loosely attached biota, such as a storm scouring the seagrass and other loosely attached organisms. Moderate sensitivity of some seagrass species to hydrocarbons, often more so in the presence of dispersants, has been reported in the general literature (Thorhaug and Marcus, 1987; Wilson and Ralph, 2010). However, as the 2010 survey, six months after the uncontrolled release, found the seagrass in excellent apparent health, a delayed effect from the uncontrolled release resulting in a change sometime between 6-18 months afterward seems unlikely. An analysis of images from the same locations between the two years supported the hypothesis that a physical scouring event was responsible, as not just seagrass cover but the abundance *Halimeda* and didemnid ascidians in the same mixed rubble and coarse sand areas were also reduced markedly. Nonetheless based on available BOM track data, there was no evidence of a cyclone directly disturbing Vulcan Shoal during the period in question. A variety of other agents of rapid change in the seagrass community were considered, including possible predation by an out breaking population of urchins or thermal stress due to abnormal sea water temperature events. In East Africa highly dense aggregations of the urchin *Tripneustes gratilla* have overgrazed entire beds of the dominating seagrass *Thalassodendron ciliatum* (Eklof et al, 2009). This is the same species of seagrass found in abundance on Vulcan Shoal in 2010. Analysis of 2010 and 2011 images for urchins found no evidence for large populations of any urchins on Vulcan Shoal, bearing in mind images were mostly collected during daylight and represent brief temporal snapshots. A

potential role of seawater surface temperature (SST) abnormalities also cannot be excluded as seagrass is also vulnerable to thermal stress (Cambell et al, 2006). Analysis of satellite temperature data of monthly SSTs for a 1-degree box centered on location 12.5S, 124.5E (http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCEP/.EMC/.CMB/.GLOBAL/.Reyn_SmithOIv2/.monthly/.sst/) does reveal unusual variation in the 2010-2011 period when compared to the preceding 30 year record. An initial summation of monthly SST near Vulcan Shoal over decadal time scales (J. Lough pers. comm. to A. Heyward) indicates regular warm and cool SST anomalies have occurred, but with the period 2010-11 sustaining an abnormally long elevated SST period, followed by a precipitous change to abnormally cool SST. The causes of the seagrass loss on Vulcan Shoal remain speculative and more detailed analysis of data available may provide an explanation. These could include a detailed storm history analysis and a comparison of sea surface temperature history. At the same time, future monitoring of Vulcan would provide an opportunity to study recovery for this major disturbance.

The gradient analysis showed no particular spatial pattern in the abundance and diversity for major benthic groups in relation to exposure to the uncontrolled release. The three hydrocarbon exposure variables; 1) oil residence time; 2) distance from uncontrolled release; 3) hydrocarbon concentration in sediment, were introduced into the GAMM analysis. This allowed a relative ranking of any potential affect of the Montara uncontrolled release, noting that the sediment hydrocarbon levels do not necessarily relate to Montara, given other potential sources in the region (see Chapter 2).. However, none of the three variables explained significant variability in benthic composition. Ascidian and Pocilloporidae were the only two benthic species with an exposure variable included in the best model. This model, however, was not significantly different from another where the hydrocarbon exposure variable was excluded. Nonetheless, a change in the relative ranking of the results when analysis were run using finer taxonomic groups suggest that any effect is more likely to be operating on small taxonomic groups or individual species rather than the whole benthos. In corals, for example, across taxa there is evidence for different sensitivities to thermal stress that results in bleaching. In addition, the response of individual species and genera may be influenced by past disturbance history (Guest et al, 2012). At the overall community level the interactions are likely to swamp any such effect if a minority of species in a particular functional group demonstrate a response. It is worth considering the possibility of effects occurring in a minor component of the benthic community that could not be detected with the current sampling methods. In order to provide a definitive resolution, species level data is likely to be required (see also Chapter 4, which uses fish data at species level).

The data captured from the nine shoals used here in the Montara study provide a foundation for an excellent regional baseline into the future. However, robust baselines need to also include data on natural temporal and spatial variability, which studies of emergent coral reefs in this region show can be very significant at decadal time scales (e.g . Smith et al, 2008). Future changes in these submerged shoals warrant monitoring to better understand key processes influencing the status of their biological communities, such as examining the possible causes, and any future recovery, of seagrass at Vulcan Shoal. The statistical modelling and predictive mapping approach developed for this project is objective, and robust and includes a quantitative assessment of spatial uncertainty. As such, these models can now be generated for new shoals using multibeam combined with localised validation data sets. These statistical models and mapping outputs will greatly assist further monitoring and the characterisation of additional shoals in the bioregion.

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Appendix 3A: Analysis of sub-sampling intensity, comparing 5,10,15 and 20 points for photo analysis, using 2010 Vulcan and Barracouta shoal transect data.

Analysis of 2010 towvid photos along the towvid transects at Vulcan (19 transects) and Barracouta (20 transects) shoals, comparing the use of 5, 10, 15 and 20 points per photo, indicated that major patterns of biotic distribution and transect proportion abundance are very similar represented by these various sampling intensities. There are some subtle differences between how some biotic groups are represented, however, to what extent these differences are interpretable is unknown. More details of analysis outcomes are summarised below

a) Correlation analysis (Table 3.1A) show a comparison of the proportional relationships of biota along transects was overall very similar (Table 3.1A) using both normal and rank correlations.
b) The total number of biotic groups detected using 20 points detected 7 more biotic groups compared the lowest sampling intensity (5 points, Table 3.2A). However in all cases these additional groups found in the 20 point images were at trace levels (very rare and occurred in very low abundances).
c) Rarefaction curves (Figure A3.1 a-d) indicate that overall 20 points does have some higher sensitivity to detect species occurrences over fewer transects but overall the number of biotic (taxa) detected was very comparable

Multivariate pattern analysis of distribution of biota over transects and using 20 verses 15, 10 and 5 points produced very similar major patters (Figures A3.2, A3.3, A3.4). This was regardless of method i.e non-Euclidian distance based cluster analysis (Figure A3.1 a-d), non Metric Multidimensional (nMDS) (Figure A3.2 a-d) and Euclidean based Principal Components Analysis (PCA) (Figure A3.3 a-d). Multivariate analysis also showed that the biotic drivers for classification of sites were also similar in magnitude and effect using 5, 10, 15 or 20 points as shown by PCA biplot (i.e Figure A3.3 a-b). All point sampling intensities produces robust patterns with a range of multivariate analysis. This is indicated by high explained variances in PCA axis 1 and 2 explaining > ~ 50% of variance in data. Similarly, nMDS produced stress values less than 0.2

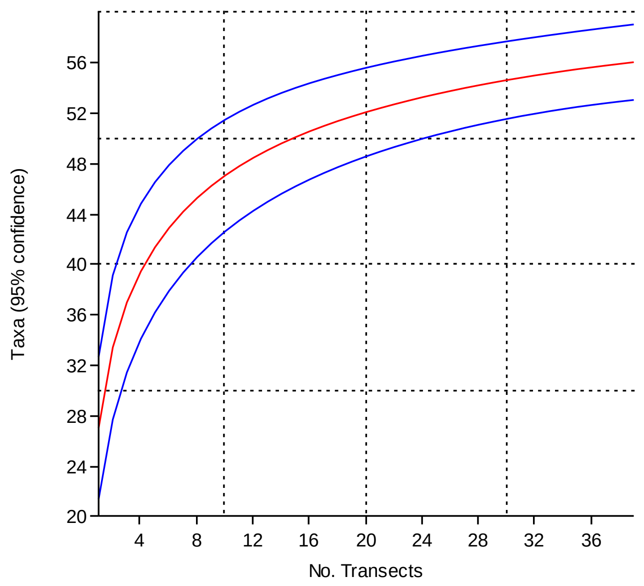
Table A3.1. Correlation analysis of proportional representation of biotic groups over transects comparing using 20 points per image with 15, 10 and 5 points per image. The results show global R statistic and all results had a highly significant F-statistic.

Comparison	Pearson's correlation R	Spearman Rank Correlation R
20 points versus 15 points	0.998	0.996
20 points versus 10 points	0.997	0.993
20 points versus 5 points	0.992	0.980

Table A3.2. The number of biotic groups detected in total over transects from both shoals comparing 20 points per image with 15, 10 and 5 points per image.

Sample effort per image	No. Biotic groups detected in total
20 Points	57
15 Points	55
10 Points	53
5 Points	49

(a)



(b)

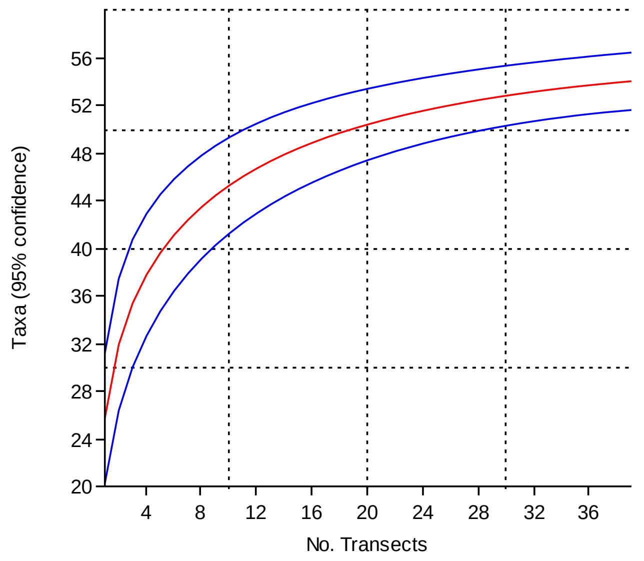
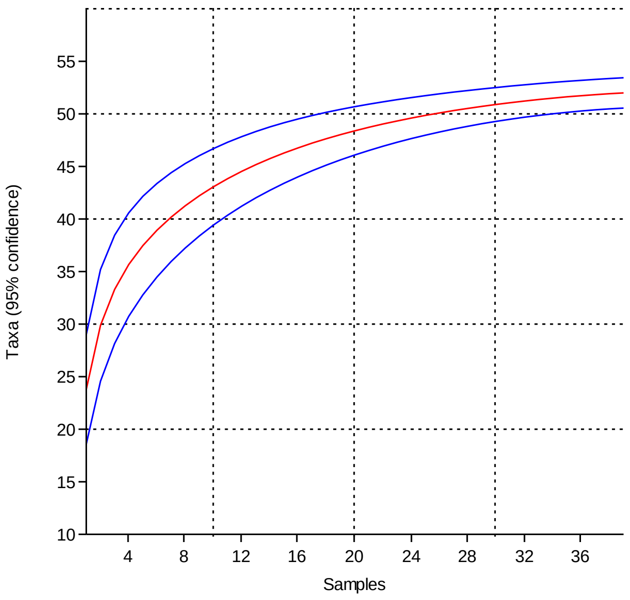


Figure A3.1. Rarefraction for CPCe analysis of Vulcan transects using a) 20 points per frame b) 15 points per frame c) 10 points per frame and d) 5 points per frame.

(c)



(d)

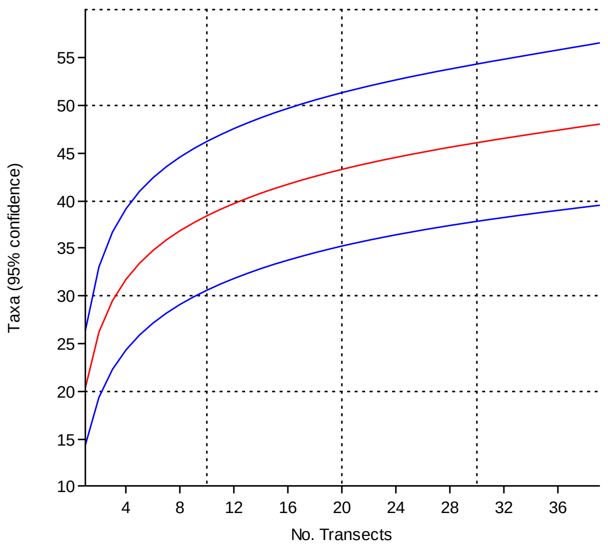
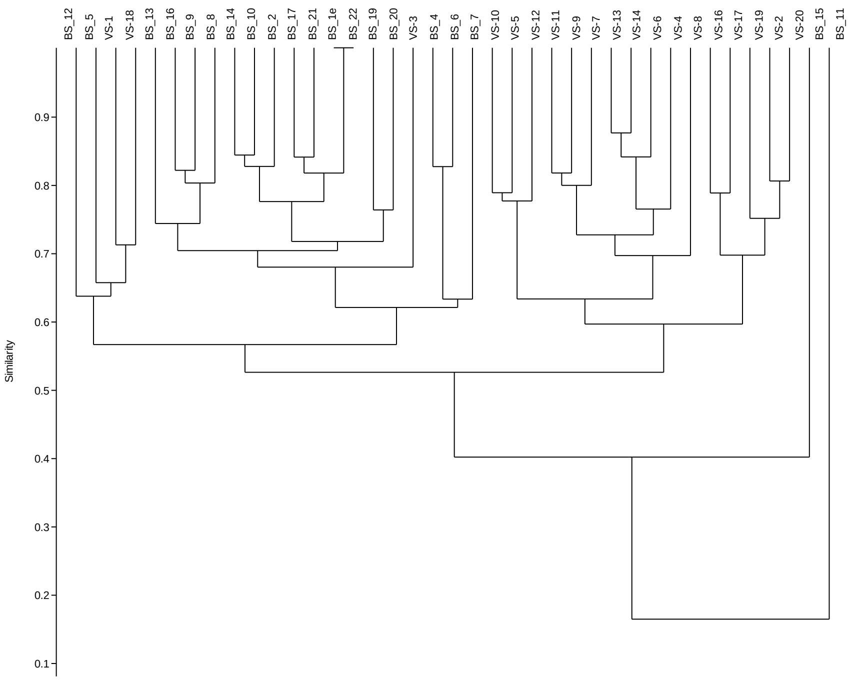


Figure A3.1 continued. Rarefraction for CPCe analysis of Vulcan transects using a) 20 points per frame b) 15 points per frame c) 10 points per frame and d) 5 points per frame.

(a)



(b)

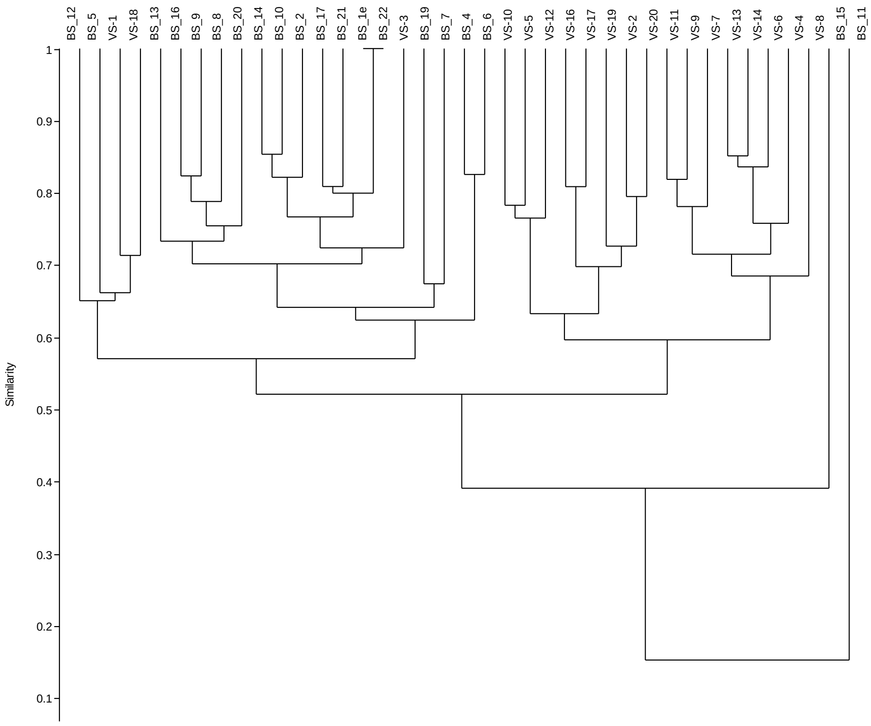


Figure A3.2. Cluster analysis (Bray-Curtis transformed data) for CPCe analysis of Vulcan transects using a) 20 points per frame b) 15 points per frame c) 10 point per frame d) 5 points per frame. Transect prefixed with "vs" our Vulcan shoal and "bs" for Barracouta shoal.

(c)

(d)

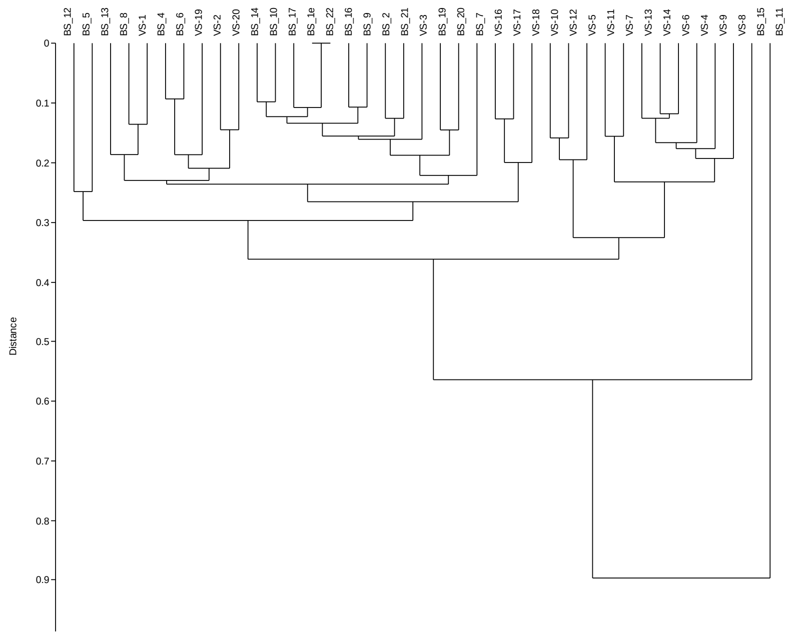
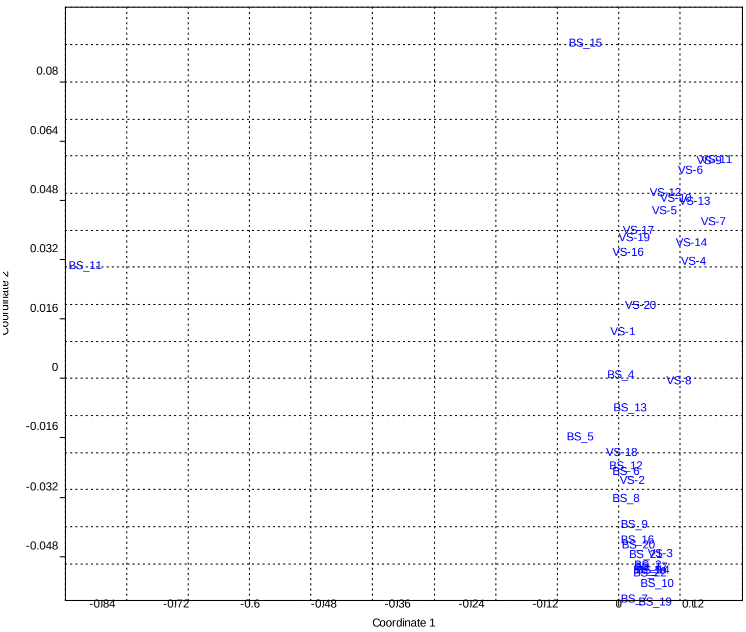


Figure A3.2 continued. Cluster analysis (Bray-Curtis transformed data) for CPCe analysis of Vulcan transects using a) 20 points per frame b) 15 points per frame c) 10 point per frame d) 5 points per frame. Transect prefixed with “vs” our Vulcan shoal and “bs” for Barracouta shoal.

(a)



(b)

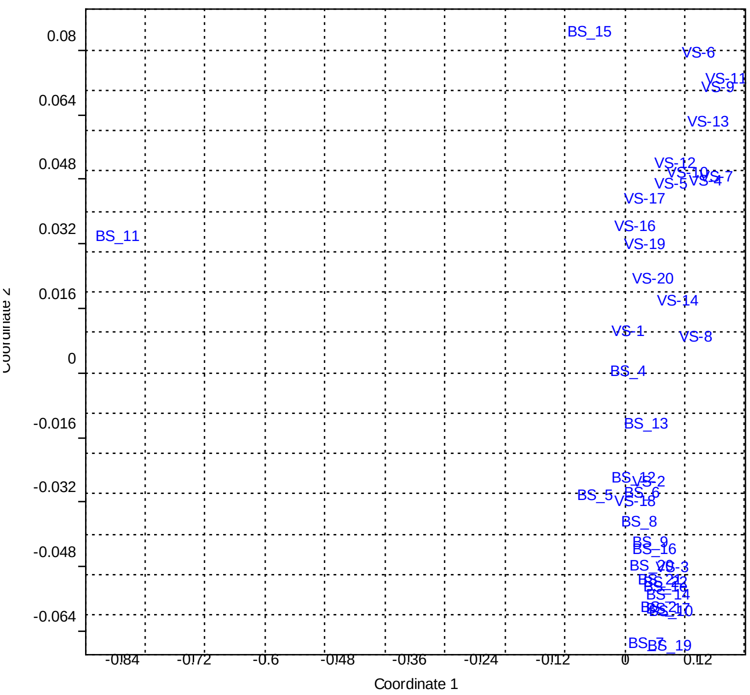
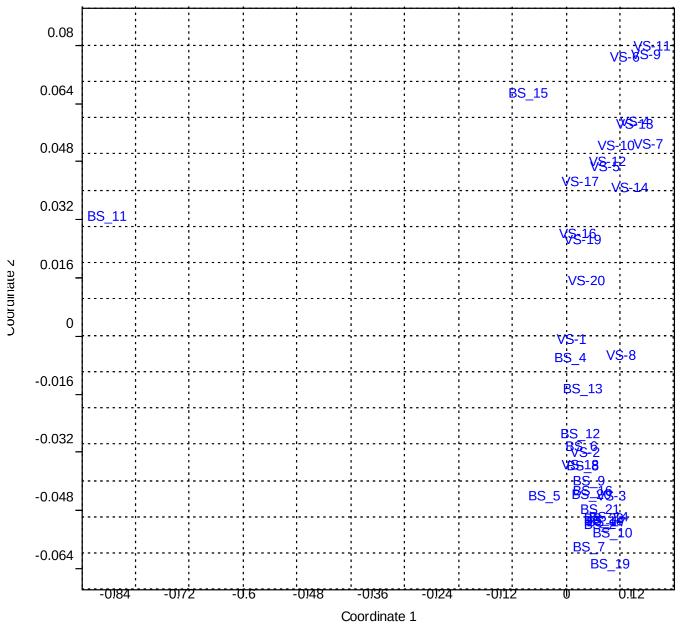


Figure A3.3. non-Metric multidimensional scaling analysis (Bray-Curtis transformed data) for CPCe analysis of Vulcan transects using a) 20 points per frame stress1 = 0.2264 b) 15 points per frame stress1= 0.2227 c) 10 point per frame strees1=0.2285 d) 5 points per frame stress1=0.2444. Transect prefixed with “vs” our Vulcan shoal and “bs” for Barracouta shoal.

(c)



(d)

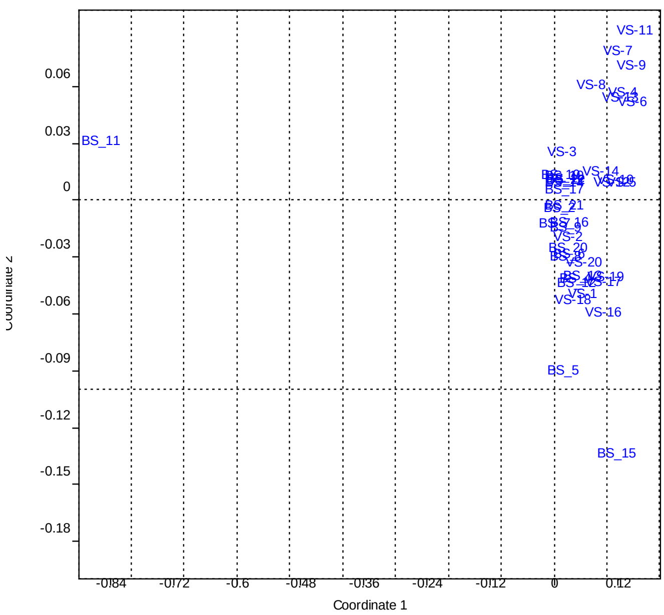
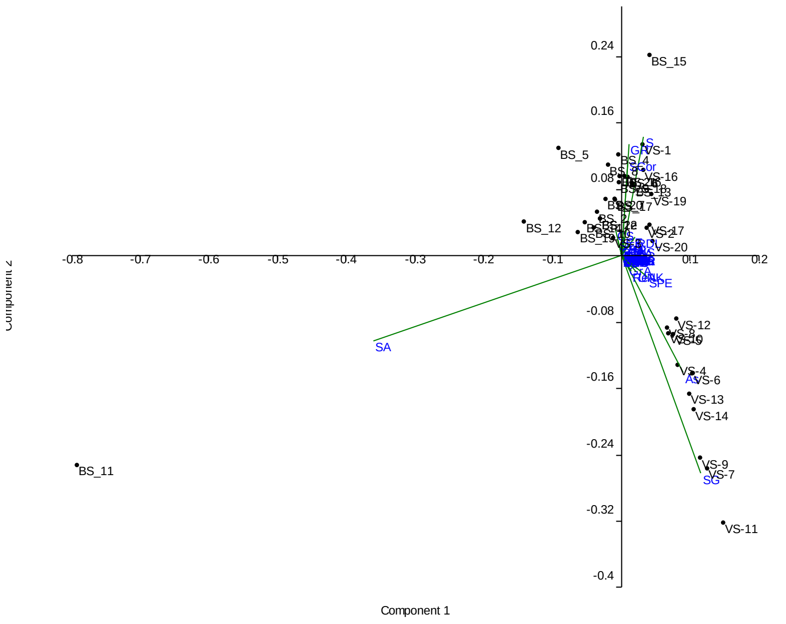


Figure A3.3 continued. non-Metric multidimensional scaling analysis (Bray-Curtis transformed data) for CPCe analysis of Vulcan transects using a) 20 points per frame stress1 = 0.2264 b) 15 points per frame stress1= 0.2227 c) 10 point per frame stress1=0.2285 d) 5 points per frame stress1=0.2444. Transect prefixed with “vs” our Vulcan shoal and “bs” for Barracouta shoal.

(a)



(b)

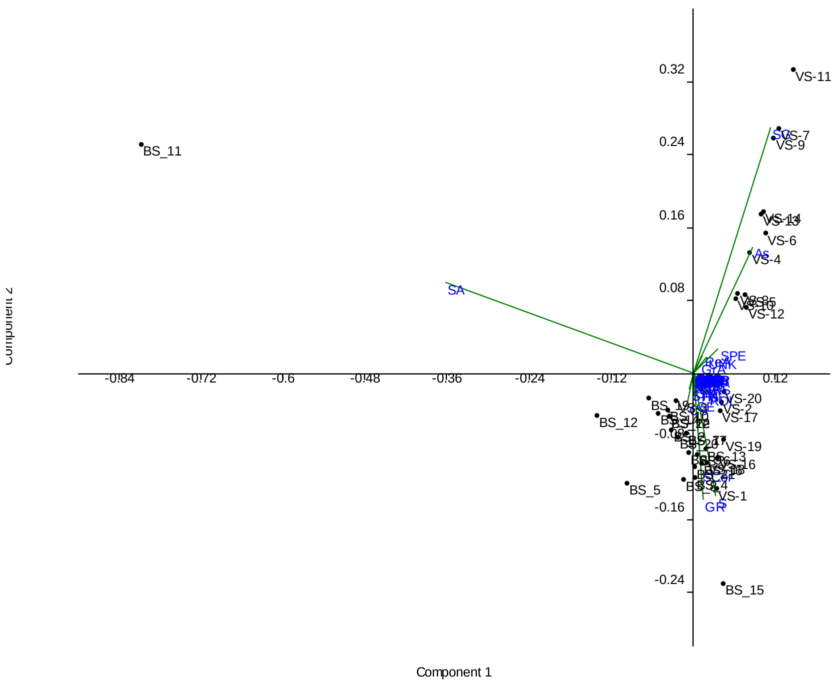
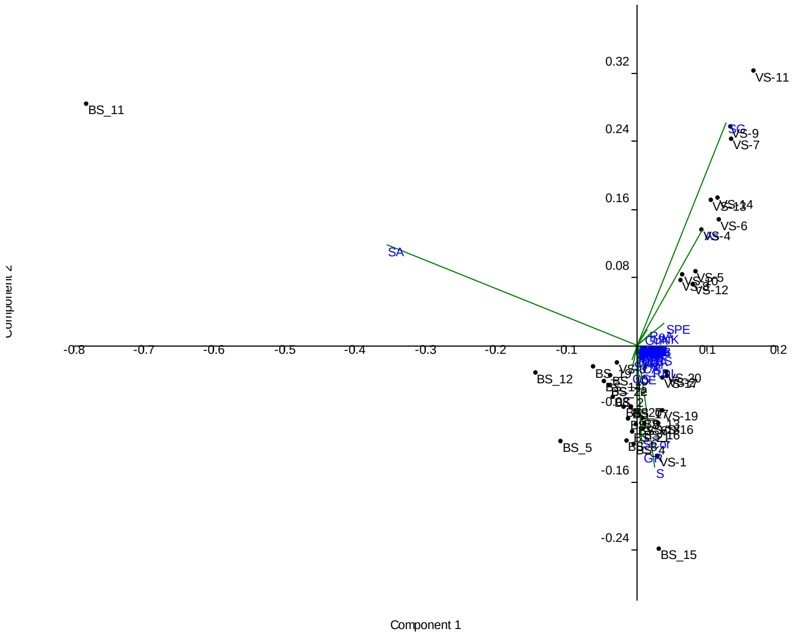


Figure A3.4. Principal component analysis (using standardized data) for Reefmon analysis of Vulcan transects using a) 20 points per frame (CP 1 = 34% explained variance, CP 2 = 24% explained variance) b) 15 points per frame (CP 1 = 32 % explained variance, CP 2 = 26% explained variance c) 10 points per frame (CP 1 = 32 % explained variance, CP 2 = 25% explained variance d) 5 points per frame (CP 1 = 30 % explained variance, CP 2 = 26% explained variance.

(c)



(d)

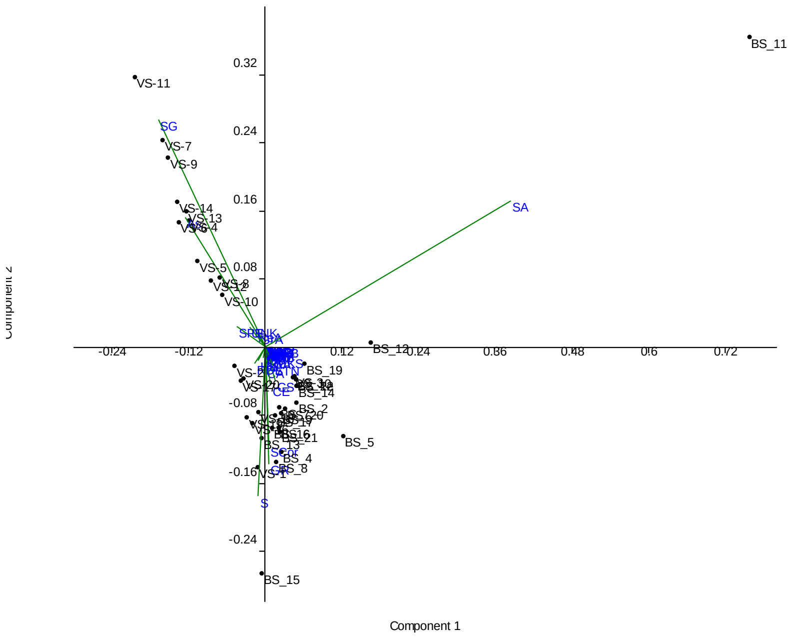


Figure A3.4 continued. Principal component analysis (using standardized data) for Reefmon analysis of Vulcan transects using a) 20 points per frame (CP 1 = 34% explained variance, CP 2 = 24% explained variance) b) 15 points per frame (CP 1 = 32 % explained variance, CP 2 = 26% explained variance c) 10 points per frame (CP 1 = 32 % explained variance, CP 2 = 25% explained variance d) 5 points per frame (CP 1 = 30 % explained variance, CP 2 = 26% explained variance.

Appendix 3B

Table B3.1. Percent cover of major benthic categories for each transect on all shoals. Refer to Figures 3.7-3.15 for transect location.

Shoal Name	Transect	Length(m)	abiotic	algae	hard coral	other	seagrass	soft coral	sponge
Barracouta East	1	2141	30.17	52.17	7.04	2.70	0.00	2.61	5.30
Barracouta East	2	1776	30.30	34.10	13.80	2.20	0.10	8.50	11.00
Barracouta East	3	1668	19.01	60.12	12.17	1.61	0.00	2.48	4.60
Barracouta East	4	1455	29.61	34.68	22.73	3.25	0.00	5.58	4.16
Barracouta East	5	1614	69.13	15.50	8.00	3.38	0.00	2.13	1.88
Barracouta East	6	1674	23.67	35.50	15.62	3.91	0.00	15.27	6.04
Barracouta East	7	1549	18.66	41.21	20.81	4.43	0.00	6.31	8.59
Barracouta East	8	1456	16.30	38.63	16.30	2.05	0.14	13.84	12.74
Barracouta East	9	831	5.74	17.66	1.70	1.06	0.00	64.47	9.36
Barracouta East	10	1229	34.71	35.43	12.57	4.71	0.00	9.71	2.86
Barracouta East	11	1391	20.00	43.54	16.64	1.95	0.00	8.14	9.73
Barracouta East	12	1225	24.81	48.87	9.62	1.35	0.00	4.66	10.68
Barracouta East	13	1279	26.57	53.88	7.76	0.60	0.00	1.79	9.40
Barracouta East	14	1018	20.70	39.30	15.65	0.87	0.00	6.96	16.52
Barracouta East	15	1458	41.99	48.45	0.50	1.86	0.00	0.75	6.46
Barracouta East	16	1188	26.30	49.29	10.24	2.52	0.00	2.99	8.66
Barracouta East	17	2352	41.89	51.50	1.46	0.43	0.09	0.69	3.95
Barracouta East	18	1205	25.35	34.65	20.94	1.10	0.00	5.20	12.76
Barracouta West	1	1207	16.27	74.40	3.87	1.60	0.00	1.60	2.27
Barracouta West	2	1602	35.10	47.80	8.80	2.20	0.00	2.00	4.10
Barracouta West	3	1901	37.17	48.30	7.64	0.94	0.00	2.83	3.11
Barracouta West	4	610	67.16	17.61	8.36	0.60	0.00	3.58	2.69
Barracouta West	5	675	43.87	37.74	11.29	0.97	0.65	1.61	3.87
Barracouta West	6	730	42.50	49.06	3.44	0.94	0.00	1.88	2.19
Barracouta West	7	1438	32.31	59.01	2.09	1.10	0.00	3.74	1.76
Barracouta West	8	1129	54.41	38.88	2.38	0.42	0.00	2.24	1.68
Barracouta West	9	2114	31.50	52.87	7.04	0.97	0.00	3.64	3.97
Echuca	1	1006	20.81	39.60	14.34	4.24	0.00	9.29	11.72
Echuca	2	1944	29.22	55.69	6.23	3.47	0.00	1.68	3.71
Echuca	3	2476	8.64	49.25	10.25	6.73	0.00	3.92	21.21
Echuca	4	2353	6.16	75.07	3.60	4.83	0.00	0.95	9.38
Echuca	5	2355	18.80	47.10	16.59	4.70	0.00	3.78	9.03
Echuca	6	2784	23.00	57.25	3.25	2.08	0.00	0.42	14.00
Echuca	7	2219	14.30	45.47	14.92	3.20	0.00	5.00	17.11
Echuca	8	1470	33.93	50.65	5.27	4.48	0.00	1.00	4.68
Echuca	9	1230	39.64	49.70	5.33	3.03	0.00	1.33	0.97
Echuca	10	1446	6.30	51.25	17.26	7.12	0.00	2.07	16.01
Echuca	11	2100	20.25	59.24	6.24	5.10	0.00	1.02	8.15

Echuca	12	2085	12.89	46.49	13.87	6.13	0.00	5.60	15.02
Echuca	13	974	7.10	42.43	14.58	5.05	0.00	3.74	27.10
Echuca	14	1979	30.83	52.19	5.52	5.42	0.00	1.15	4.90
Echuca	15	1966	3.14	69.74	3.14	5.55	0.00	0.63	17.80
Echuca	16	1473	10.26	54.09	18.26	2.96	0.00	1.74	12.70
Eugene McDermott	1	911	30.68	44.55	14.55	1.82	0.00	2.05	6.36
Eugene McDermott	2	1735	25.83	50.83	7.71	8.13	0.00	1.88	5.63
Eugene McDermott	3	847	8.68	40.87	28.39	3.25	0.00	2.89	15.91
Eugene McDermott	4	1146	14.14	38.80	23.16	4.81	0.00	9.02	10.08
Eugene McDermott	5	972	34.08	42.72	4.00	4.96	0.00	1.60	12.64
Eugene McDermott	6	1107	1.93	61.38	22.62	3.31	0.00	6.07	4.69
Eugene McDermott	7	1237	5.82	51.64	30.18	2.18	0.00	2.55	7.64
Eugene McDermott	8	1879	2.62	32.62	24.76	2.62	0.00	16.67	20.71
Eugene McDermott	9	1324	20.06	43.56	23.50	3.14	0.00	3.14	6.59
Eugene McDermott	10	1151	18.00	44.00	22.00	0.00	0.00	4.00	12.00
Eugene McDermott	11	2248	26.28	47.52	13.72	3.86	0.00	1.72	6.90
Eugene McDermott	12	1443	40.11	43.26	5.06	1.91	0.00	0.67	8.99
Eugene McDermott	13	1292	2.47	65.39	7.30	8.43	0.00	0.67	15.73
Eugene McDermott	14	1823	11.27	37.96	29.14	3.76	0.00	10.20	7.67
Eugene McDermott	15	802	9.52	36.67	11.67	5.48	0.00	17.14	19.52
Eugene McDermott	16	765	5.98	27.48	28.04	2.62	0.00	24.67	11.21
Eugene McDermott	17	1231	16.55	30.07	18.42	2.45	0.00	28.92	3.60
Eugene McDermott	18	997	21.20	41.00	4.40	6.80	0.00	1.00	25.60
Goeree	1	1486	20.00	41.64	24.64	4.18	0.00	5.18	4.36
Goeree	2	986	8.99	45.07	25.51	2.61	0.00	6.81	11.01
Goeree	3	879	22.15	52.48	8.72	9.40	0.00	0.81	6.44
Goeree	4	1701	10.05	67.40	11.05	6.39	0.00	0.27	4.84
Goeree	5	741	17.72	26.08	23.80	6.84	0.00	8.35	17.22
Goeree	6	349	48.10	34.29	2.86	1.90	0.00	1.90	10.95
Goeree	7	1349	24.94	33.15	23.71	5.06	0.00	7.19	5.96
Goeree	8	1323	19.74	60.38	5.26	8.08	0.00	0.26	6.28
Goeree	9	1347	23.31	64.08	4.46	3.31	0.00	1.27	3.57
Goeree	10	1266	6.51	70.35	14.77	4.65	0.00	0.70	3.02
Goeree	11	1172	29.50	46.33	9.93	9.78	0.00	0.29	4.17
Goeree	12	1131	30.45	50.45	8.03	6.11	0.00	1.15	3.82
Goeree	13	1341	25.35	53.94	7.46	8.87	0.00	0.42	3.94
Goeree	14	983	28.69	46.34	11.17	2.90	0.00	4.00	6.90
Heywood	1	1823	17.66	62.80	8.50	3.18	0.00	0.93	6.92
Heywood	2	1623	9.45	72.02	4.05	1.47	0.00	1.47	11.53
Heywood	3	1685	44.48	45.46	2.84	1.64	0.00	0.55	5.03
Heywood	4	742	31.90	55.95	2.78	1.27	0.00	0.51	7.59
Heywood	5	2513	38.99	52.46	0.60	1.11	0.00	0.20	6.63
Heywood	6	1659	43.72	51.66	1.61	1.01	0.00	0.70	1.31
Heywood	7	1592	32.76	55.29	2.39	1.37	0.00	1.25	6.94

Heywood	8	1851	32.45	46.35	4.46	2.15	0.00	0.94	13.65
Heywood	9	1637	56.63	33.59	3.15	1.74	0.00	0.65	4.24
Heywood	10	1399	18.84	60.90	6.19	3.23	0.00	0.77	10.06
Heywood	11	698	25.17	55.51	6.97	8.76	0.00	0.45	3.15
Heywood	12	64	8.00	64.00	2.00	2.00	0.00	0.00	24.00
Heywood	13	2311	23.40	50.55	5.36	3.40	0.00	1.62	15.66
Heywood	14	2626	39.17	34.11	13.66	6.64	0.00	2.72	3.70
Heywood	15	1488	11.23	29.16	51.87	4.77	0.00	0.26	2.71
Heywood	16	3036	18.22	27.57	44.43	0.86	0.00	2.15	6.77
Heywood	17	4462	26.34	34.40	32.63	1.13	0.00	0.29	5.21
Heywood	18	2968	78.21	18.07	1.06	1.20	0.00	0.13	1.33
Heywood	19	2073	35.10	53.92	4.41	2.35	0.00	1.18	3.04
Heywood	20	1444	30.86	63.21	1.11	0.99	0.00	0.49	3.33
Heywood	21	282	38.62	46.90	0.69	0.00	0.00	4.83	8.97
Shoal 25	1	823	23.27	53.82	13.27	4.00	0.00	2.55	3.09
Shoal 25	2	963	40.45	41.79	5.59	5.70	0.00	2.23	4.25
Shoal 25	3	1309	21.58	55.81	10.70	6.79	0.00	2.23	2.88
Shoal 25	4	1680	30.26	49.82	7.55	5.05	0.00	4.03	3.30
Shoal 25	5	1522	9.13	63.93	15.14	3.82	0.00	1.85	6.13
Shoal 25	6	1287	26.67	39.39	27.76	3.03	0.00	0.73	2.42
Shoal 25	7	659	27.38	50.24	9.52	2.14	0.00	0.95	9.76
Shoal 25	8	685	28.18	50.91	15.00	0.91	0.00	1.59	3.41
Shoal 25	9	964	6.54	48.60	20.37	2.80	0.00	18.13	3.55
Shoal 25	10	681	41.44	37.12	13.51	2.88	0.00	0.72	4.32
Shoal 25	11	623	38.33	32.78	10.56	5.28	0.00	4.44	8.61
Shoal 25	12	1459	26.57	39.72	24.69	3.47	0.09	0.85	4.60
Shoal 25	13	1152	23.46	59.69	10.05	3.66	0.10	1.05	1.99
Vulcan	1	1317	28.72	39.10	10.27	11.74	0.10	3.04	7.02
Vulcan	2	2515	48.89	32.59	5.10	5.02	0.00	4.03	4.36
Vulcan	3	1832	21.78	42.20	12.98	15.39	0.00	3.56	4.08
Vulcan	4	1263	22.41	54.04	5.82	2.41	3.40	0.99	10.92
Vulcan	5	1436	38.99	37.88	6.82	3.24	2.79	1.68	8.60
Vulcan	6	1738	47.17	30.61	7.98	6.77	0.71	2.42	4.34
Vulcan	7	1113	13.28	61.22	7.48	5.04	2.29	0.76	9.92
Vulcan	8	1259	32.40	29.77	14.22	9.97	1.61	2.93	9.09
Vulcan	9	1560	26.02	44.22	4.94	6.14	1.93	2.29	14.46
Vulcan	10	1265	49.08	33.33	6.24	6.24	0.99	0.99	3.12
Vulcan	11	1400	45.45	40.73	2.30	5.70	0.97	0.85	4.00
Vulcan	12	1604	34.49	39.07	6.64	8.13	2.34	2.80	6.54
Vulcan	13	1080	21.36	37.80	7.29	11.36	1.69	4.07	16.44
Vulcan	14	1080	25.34	39.66	13.28	10.52	0.69	5.17	5.34
Vulcan	15	1296	34.07	42.62	6.48	5.66	3.45	2.34	5.38
Vulcan	16	1405	19.62	44.40	9.31	7.92	0.88	2.01	15.85
Vulcan	17	1480	43.21	28.81	6.55	7.74	5.71	2.02	5.95

Vulcan	18	1387	36.49	41.89	6.22	5.95	3.51	3.11	2.84
Vulcan	19	1265	38.68	43.31	4.13	5.12	2.81	1.16	4.79
Vulcan	20	1226	21.03	49.56	8.24	8.82	4.26	0.29	7.79
Vulcan	21	650	49.88	12.84	9.88	7.41	1.73	2.96	15.31
Vulcan	22	1312	31.93	27.45	9.81	11.93	2.73	0.99	15.16
Vulcan	23	1277	32.76	42.99	4.41	1.73	9.61	1.57	6.93
Vulcan	24	1312	40.45	34.03	9.70	5.07	3.73	1.64	5.37
Wave Governor Bank	1	633	20.23	63.72	3.49	9.07	0.00	0.47	3.02
Wave Governor Bank	2	962	31.30	49.28	5.94	5.65	0.00	1.88	5.94
Wave Governor Bank	3	681	31.49	41.91	8.30	2.34	0.00	0.00	15.96
Wave Governor Bank	4	880	27.72	45.20	5.67	6.93	0.00	1.42	13.07
Wave Governor Bank	5	646	14.55	74.09	2.05	3.64	0.00	0.00	5.68
Wave Governor Bank	6	1197	5.48	57.19	32.89	1.33	0.00	0.44	2.67
Wave Governor Bank	7	1145	35.77	44.87	7.56	3.72	0.00	0.26	7.82

Appendix 3C: Partial response plots showing the influence of depth, slope, aspect (radians) and kernelled rugosity variables on the presence of major benthic groups and substrate types.

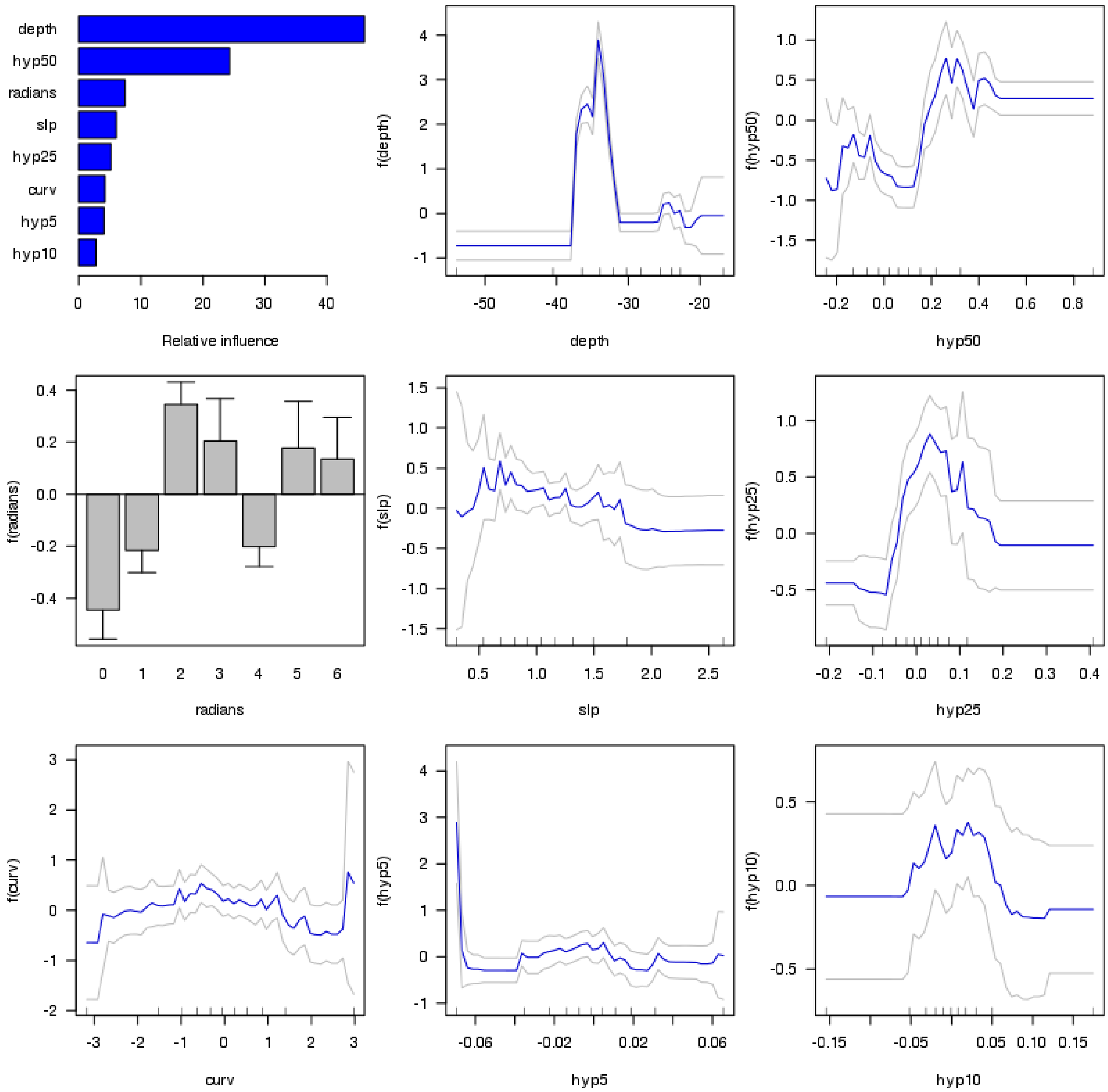


Figure C3.1: Filter feeder partial response plots. Y-axis are mean centered probability of occurrence. For details or response variables see Table 3.1.

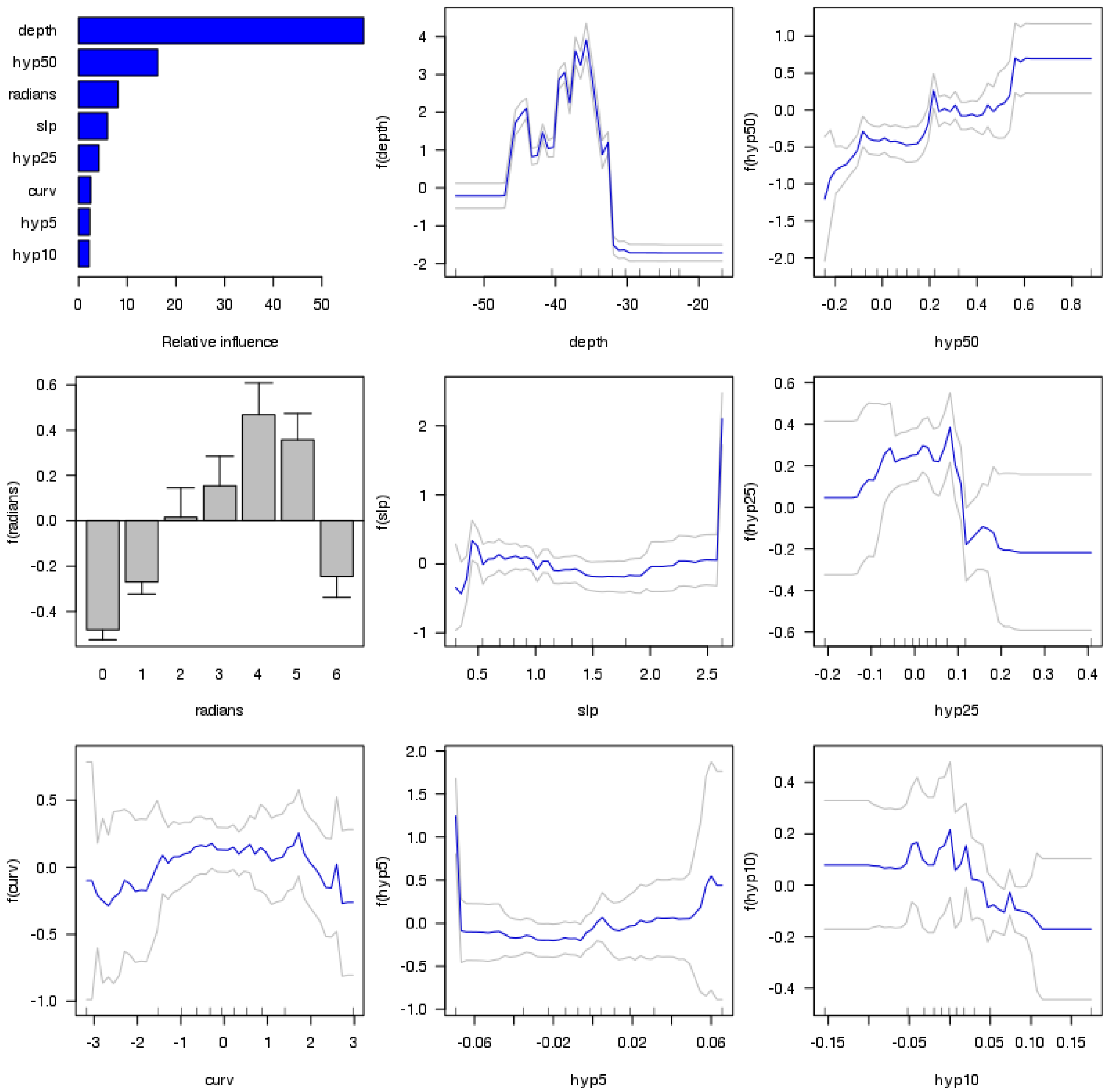


Figure C3.2. Soft coral partial response plots. Y-axis are mean centered probability of occurrence. For details or response variables see Table 3.1.

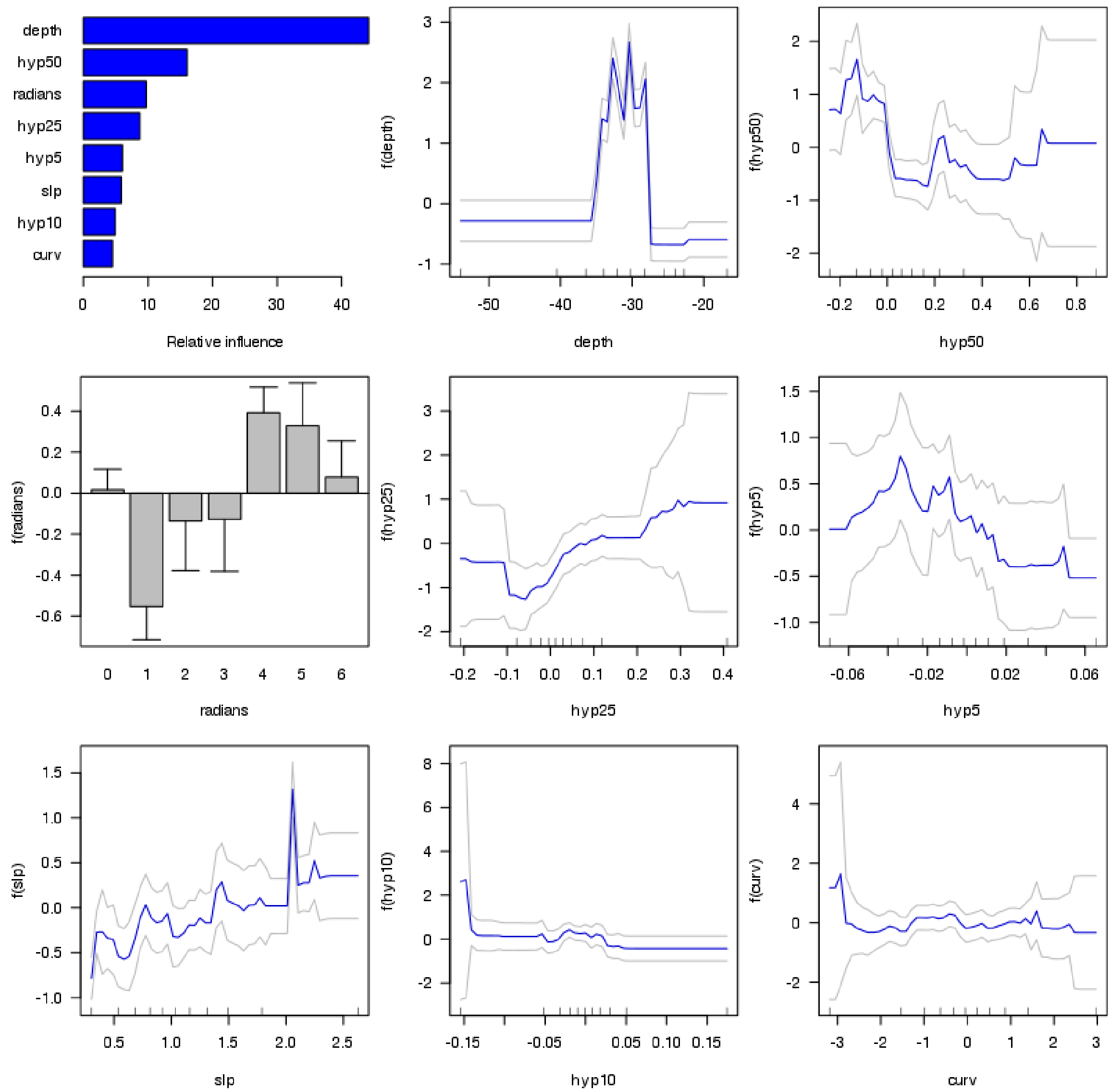


Figure C3.3. Isolates partial response plots. Y-axis are mean centered probability of occurrence. For details or response variables see Table 3.1.

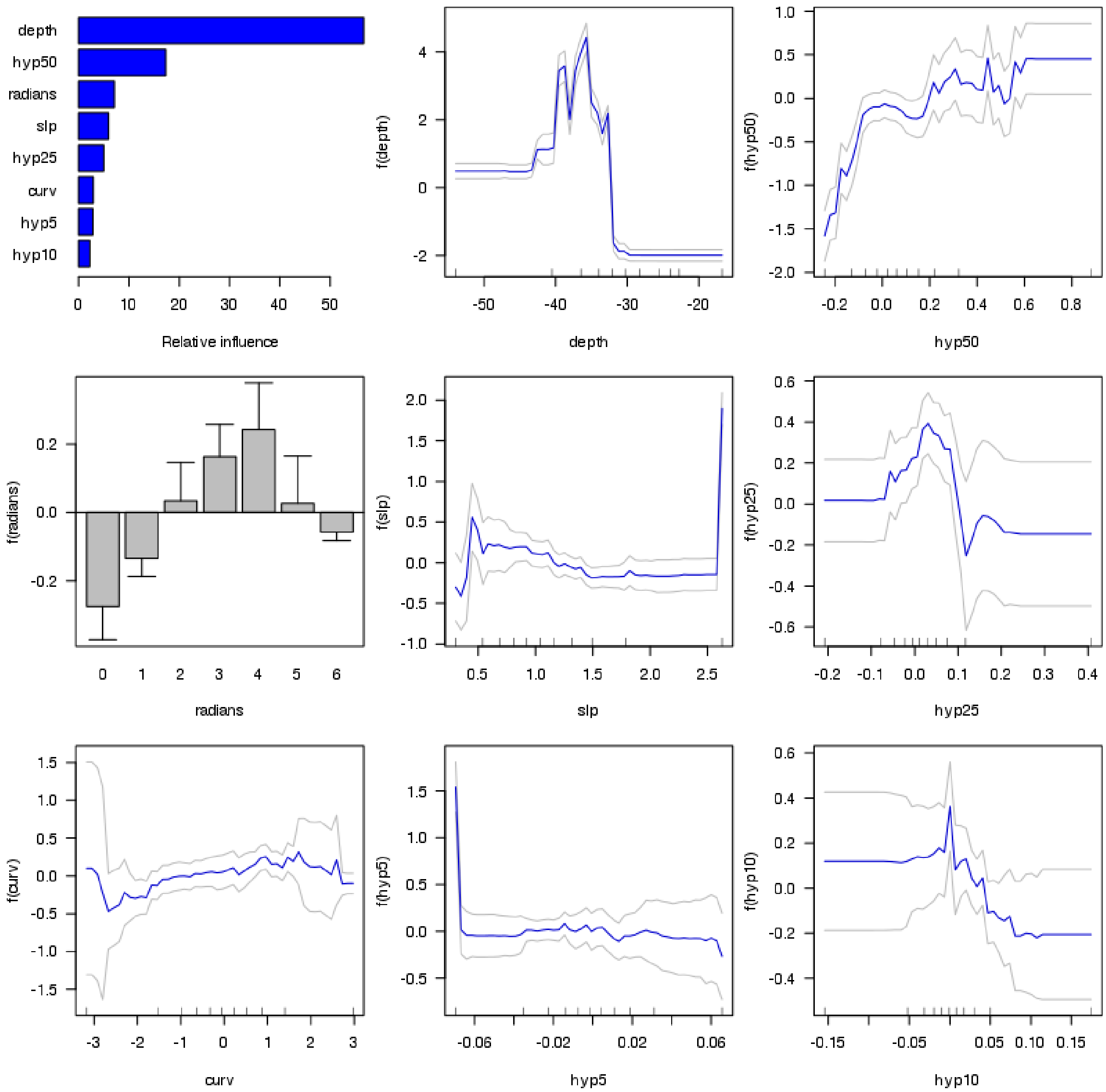


Figure C3.4. *Halimeda* partial response plots. Y-axis are mean centered probability of occurrence. For details or response variables see Table 3.1.

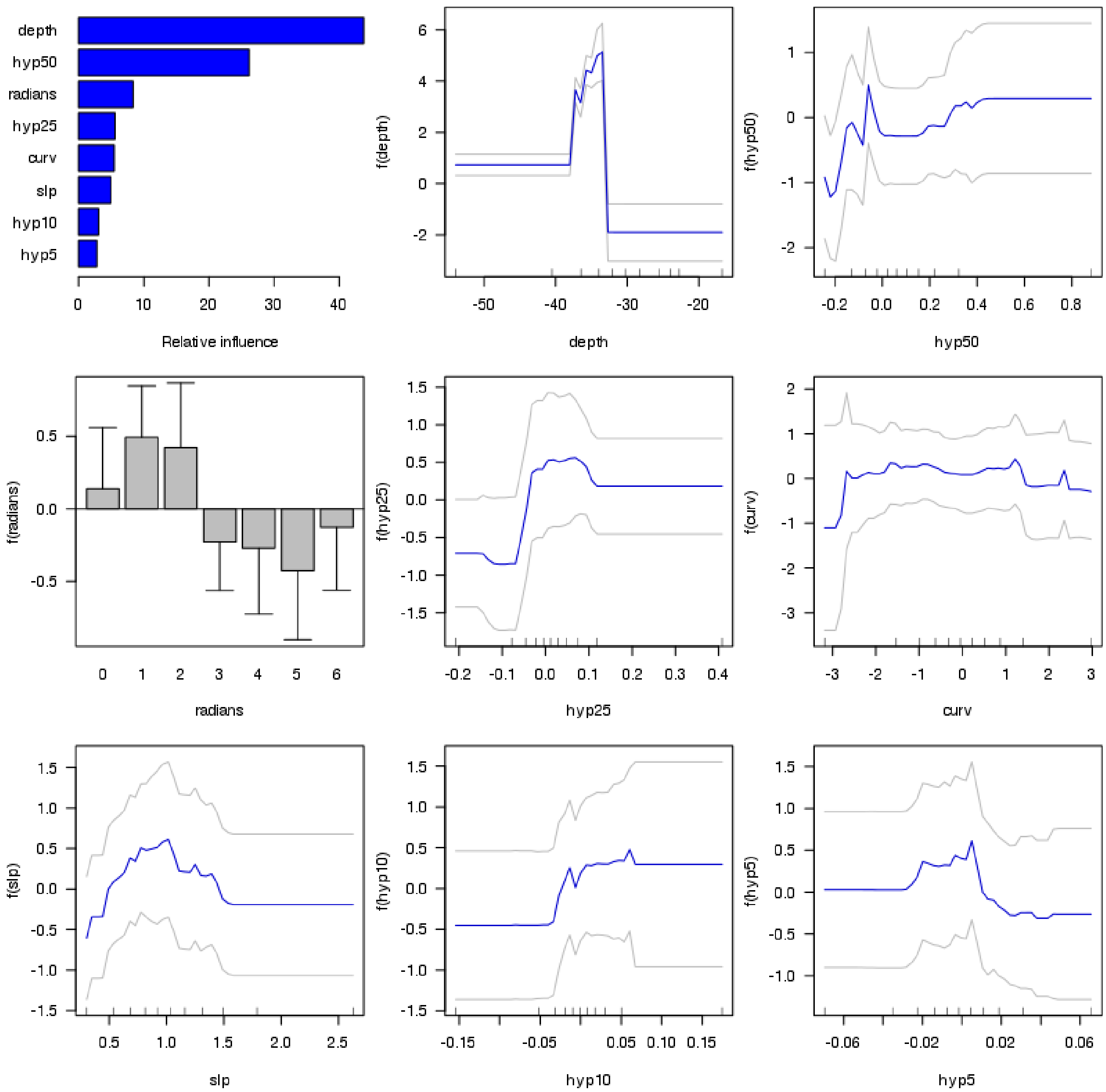


Figure C3.5. Macroalgae partial response plots. Y-axis are mean centered probability of occurrence. For details or response variables see Table 3.1.

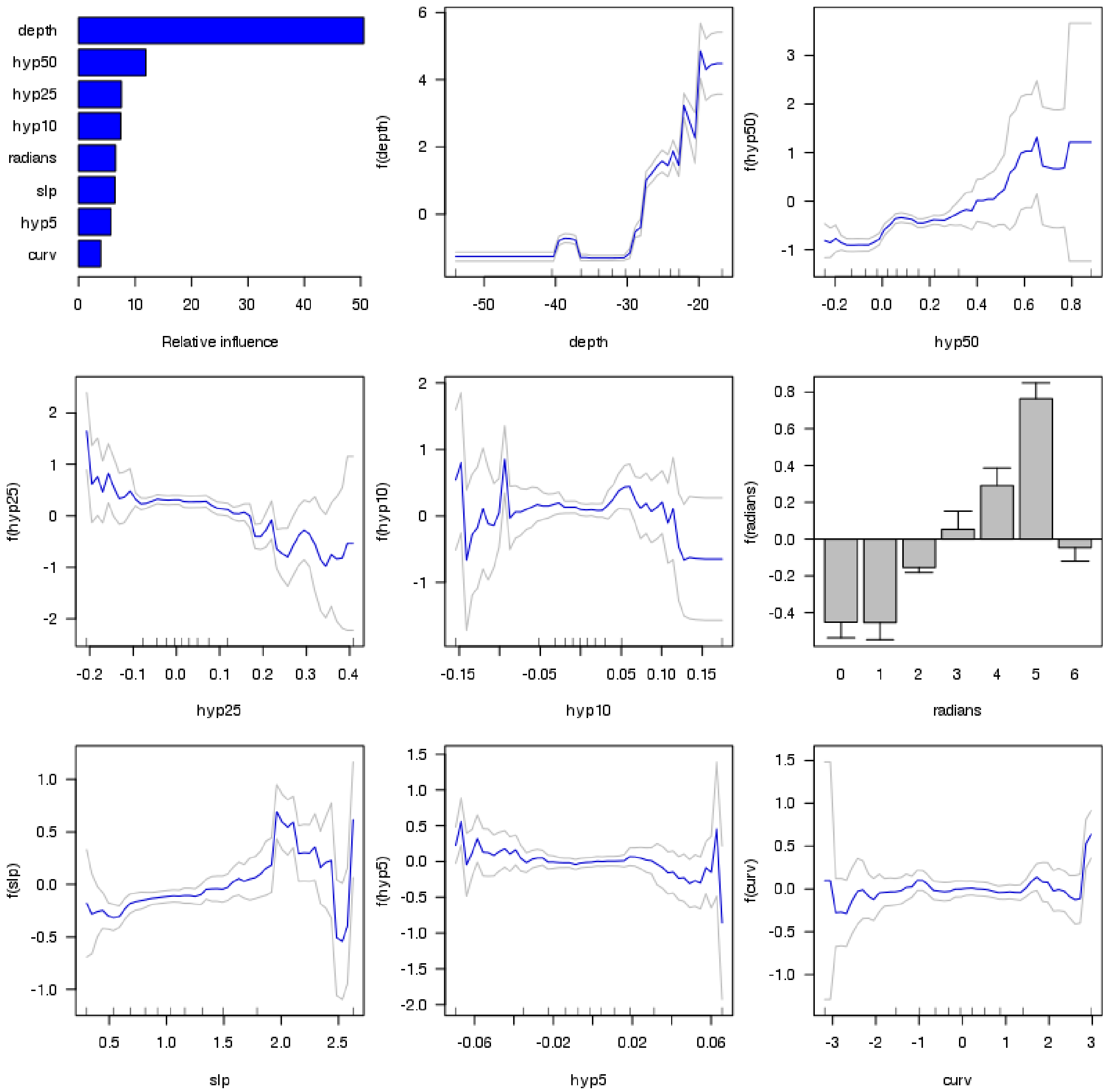


Figure C3.6. High relief limestone partial response plots. Y-axis are mean centered probability of occurrence. For details or response variables see Table 3.1.

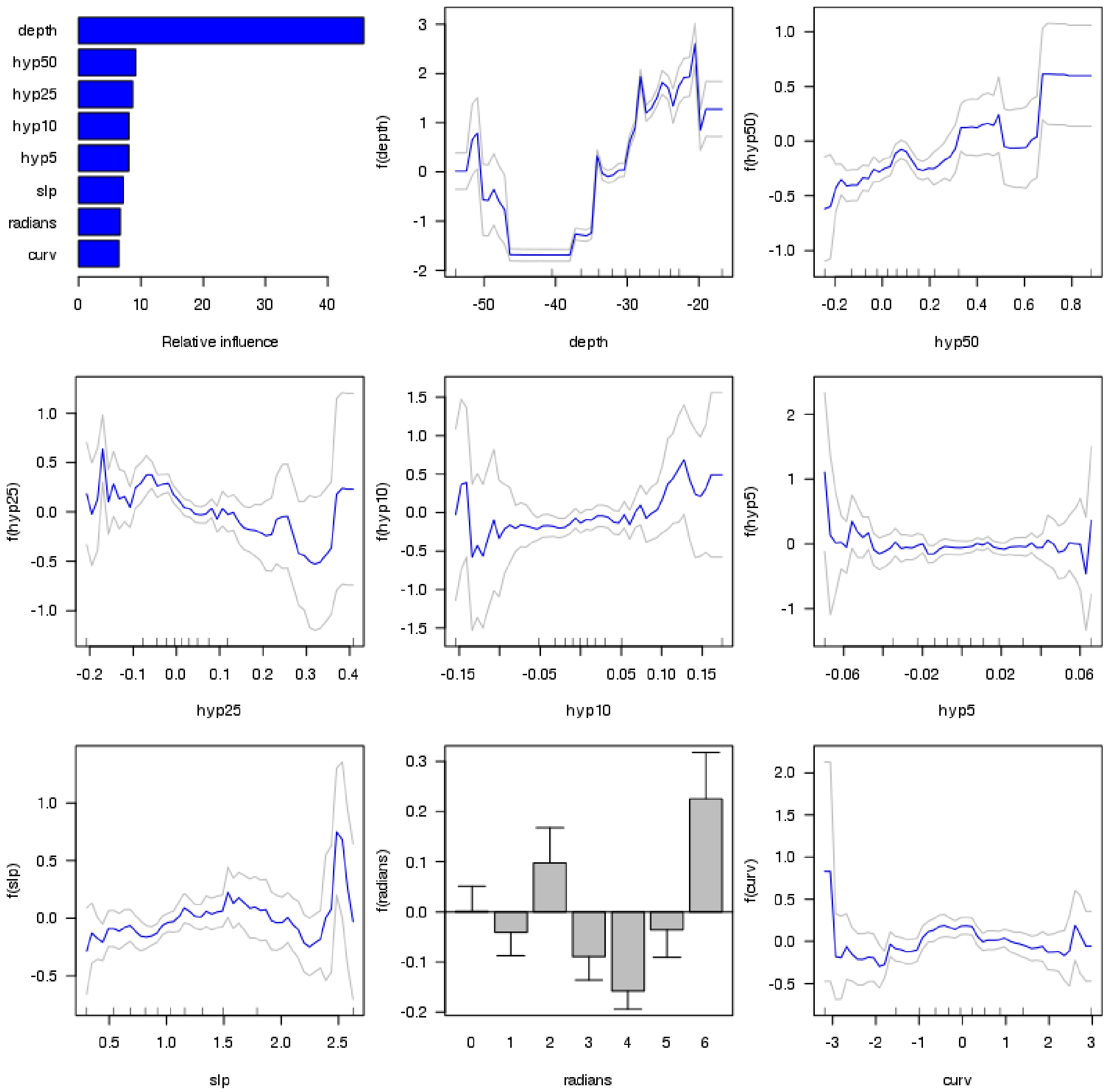


Figure C3.7. Low relief limestone partial response plots. Y-axis are mean centered probability of occurrence. For details or response variables see Table 3.1.

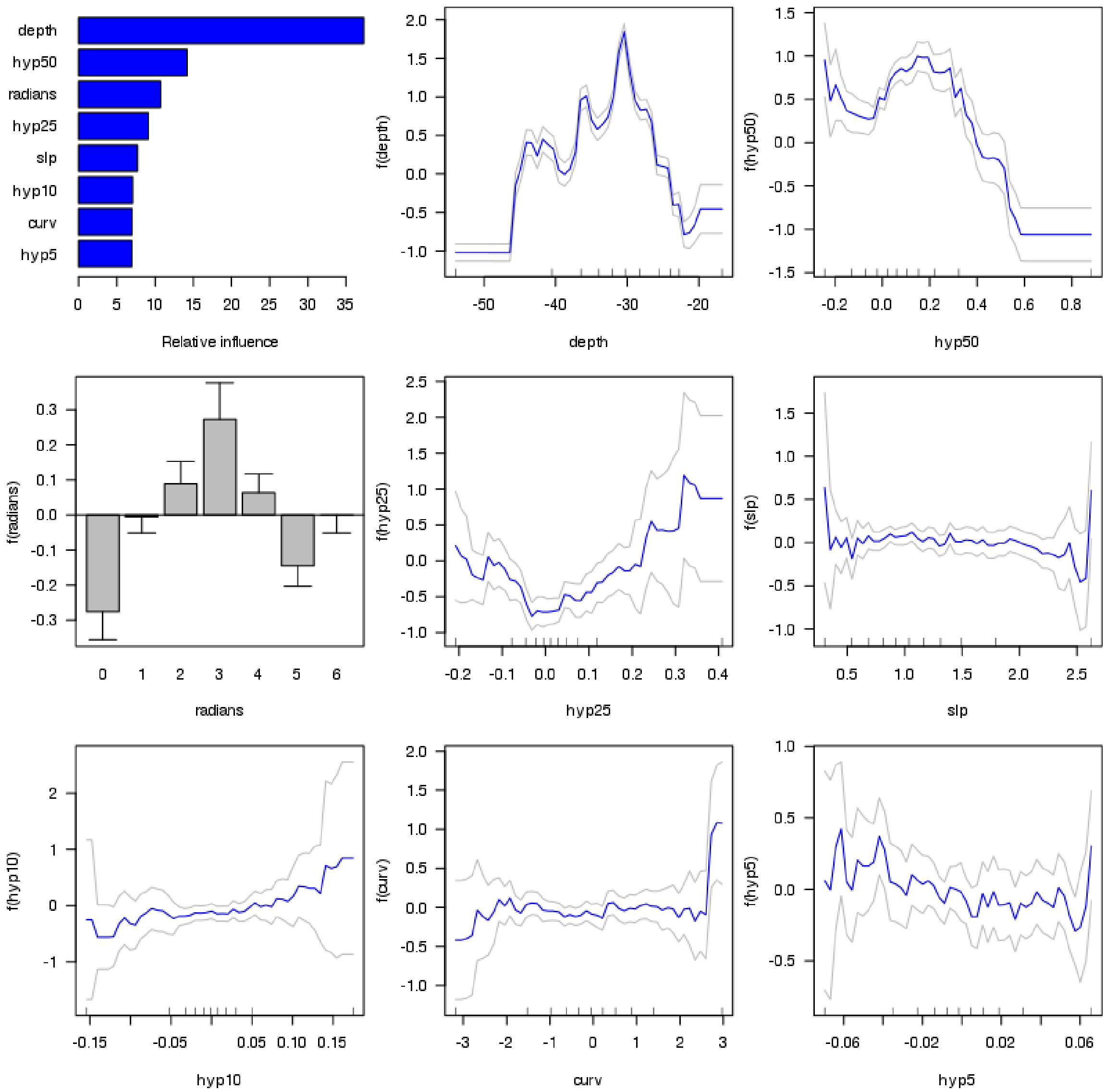


Figure C3.8. Rubble partial response plots. Y-axis are mean centered probability of occurrence. For details or response variables see Table 3.1.

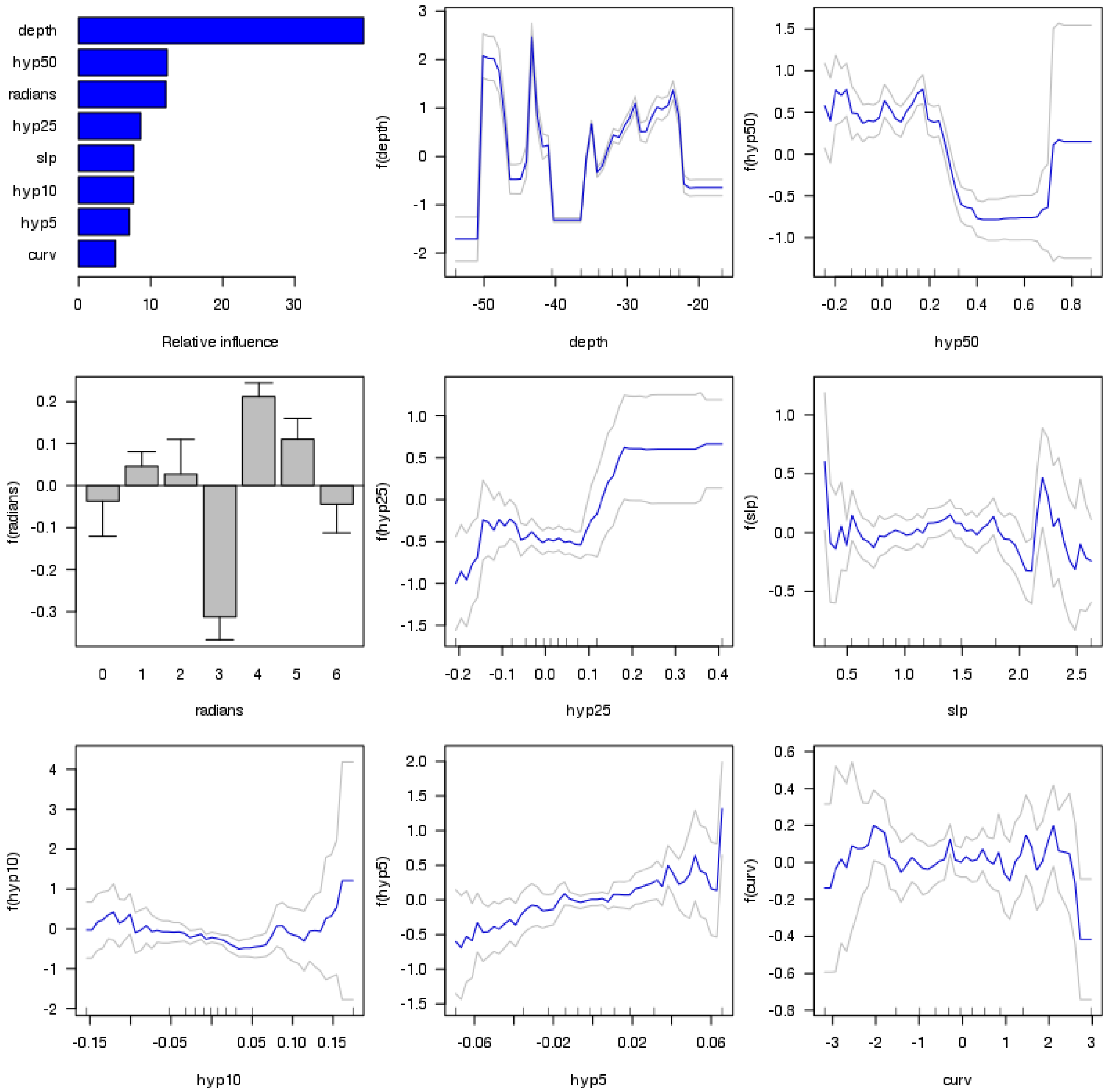


Figure C3.9. Stone and rubble partial response plots. Y-axis are mean centered probability of occurrence. For details or response variables see Table 3.1.

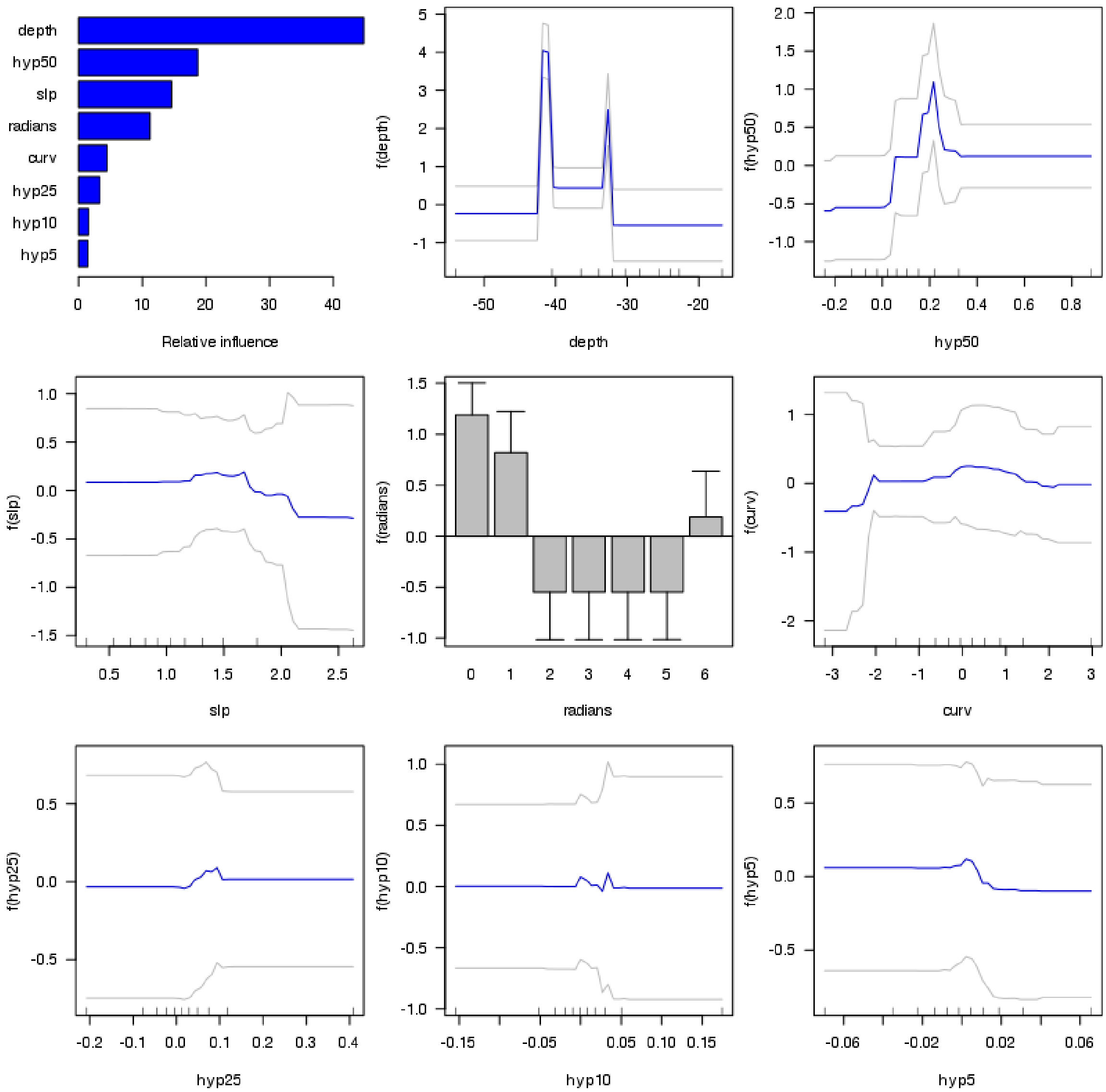


Figure C3.10. Sand partial response plots. Y-axis are mean centered probability of occurrence. For details or response variables see Table 3.1.

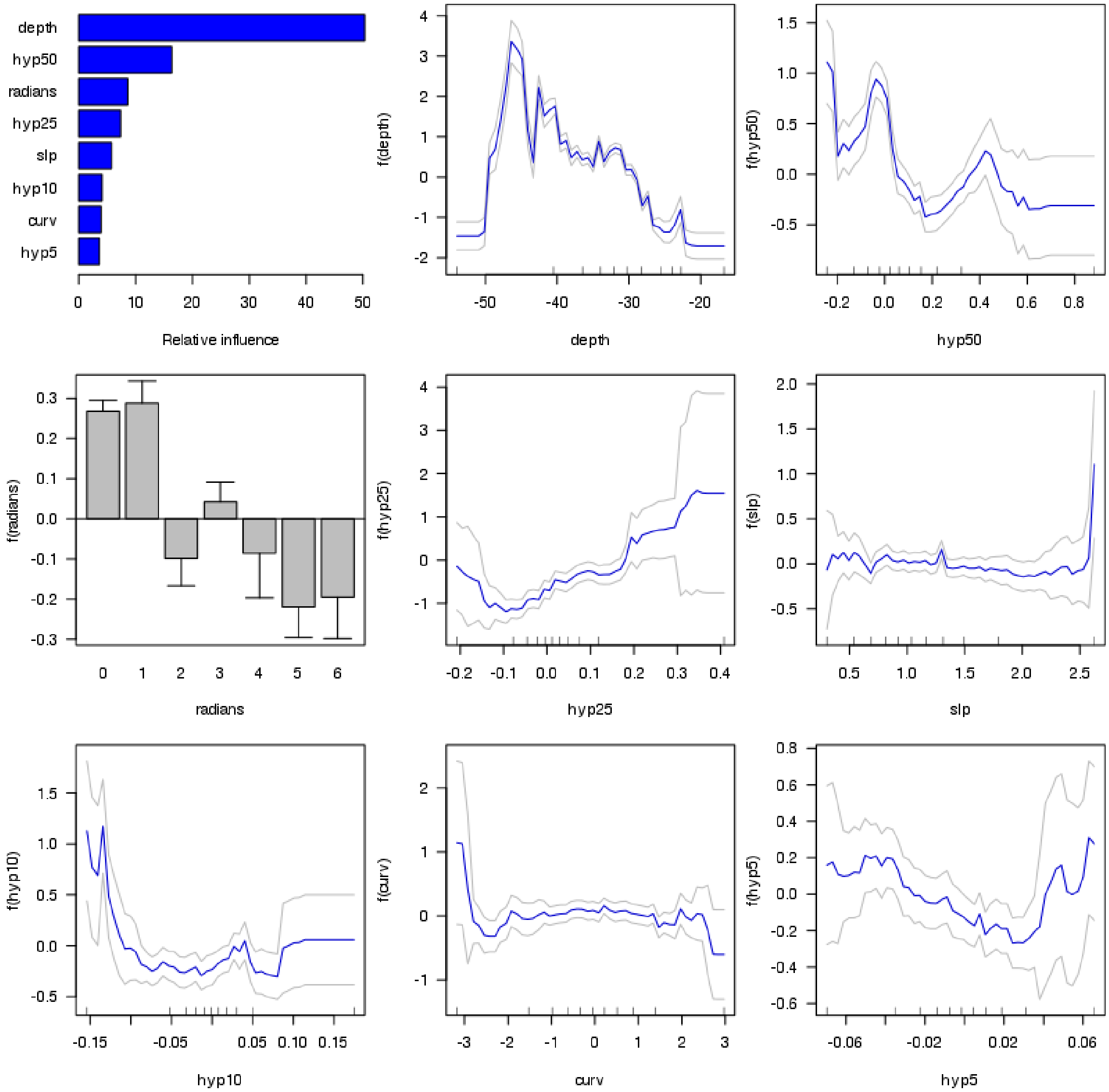


Figure C3.11. Sand and rubble partial response plots. Y-axis are mean centered probability of occurrence. For details or response variables see Table 3.1.

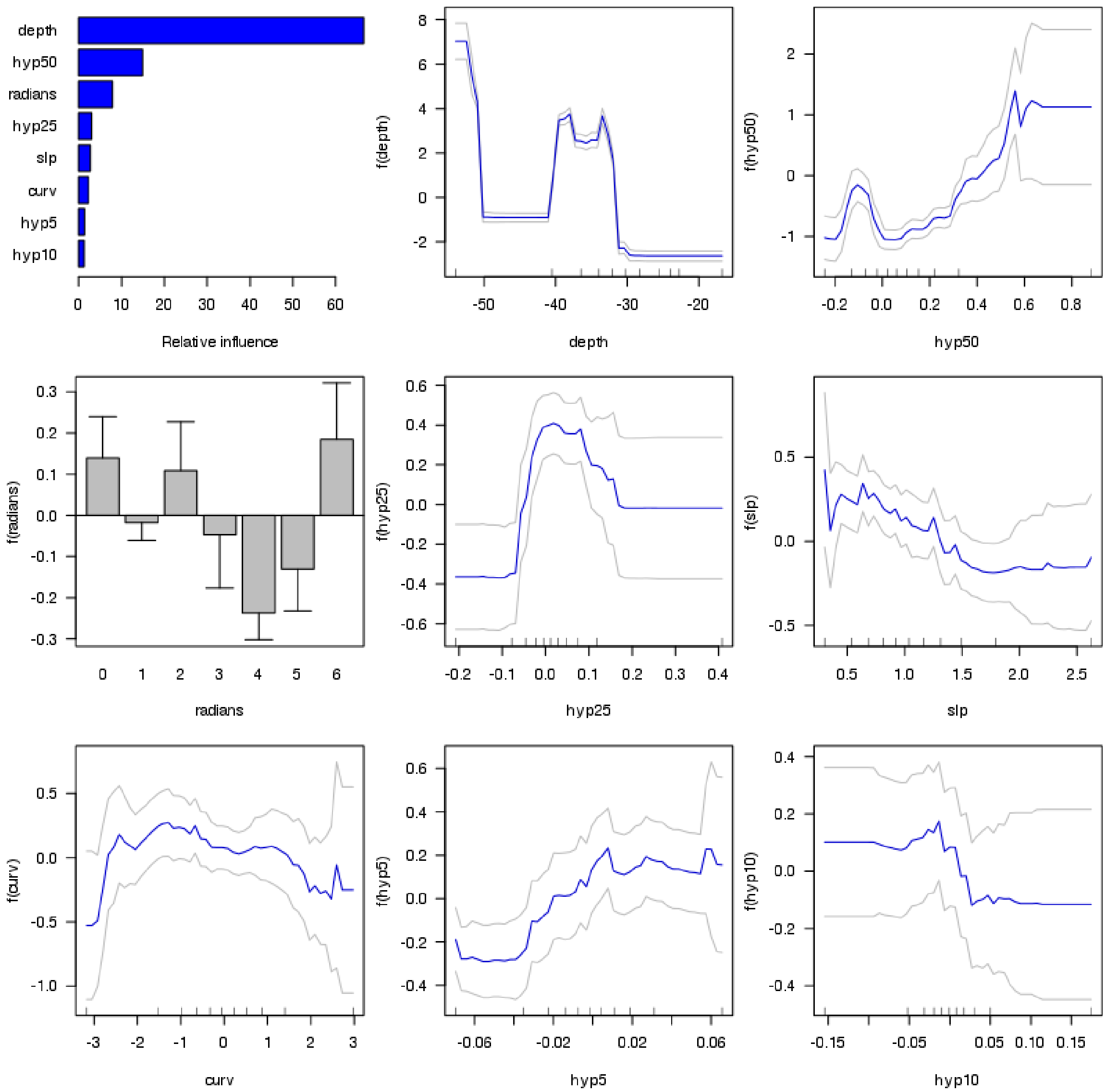


Figure C3.12. Coarse sand partial response plots. Y-axis are mean centered probability of occurrence. For details or response variables see Table 3.1.

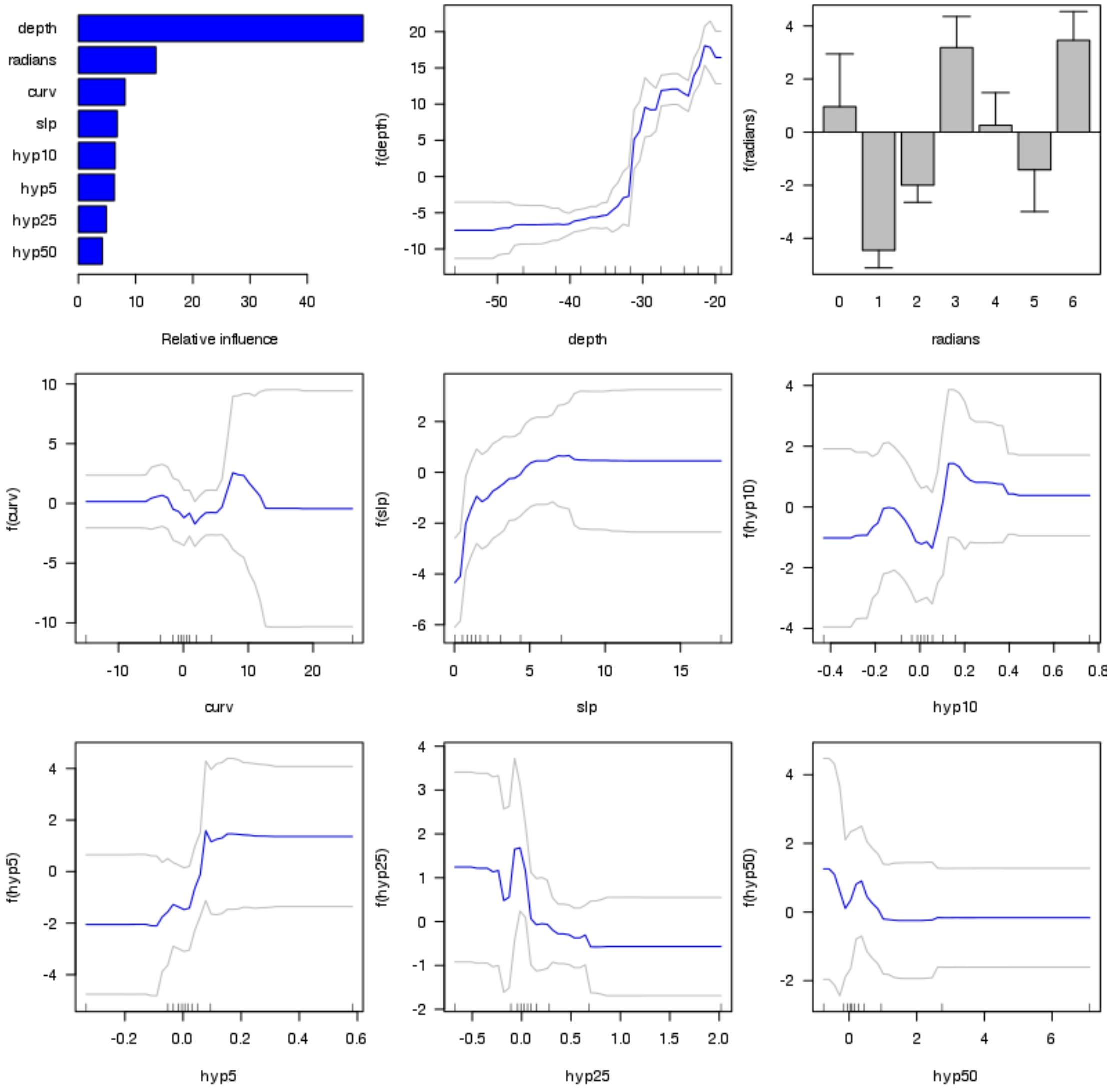


Figure C3.13. BRUVS fish species richness (total number of species n, cube root transformed) Y-axis are mean centered number of occurrences for transformed data. For details or response variables see Table 3.1.

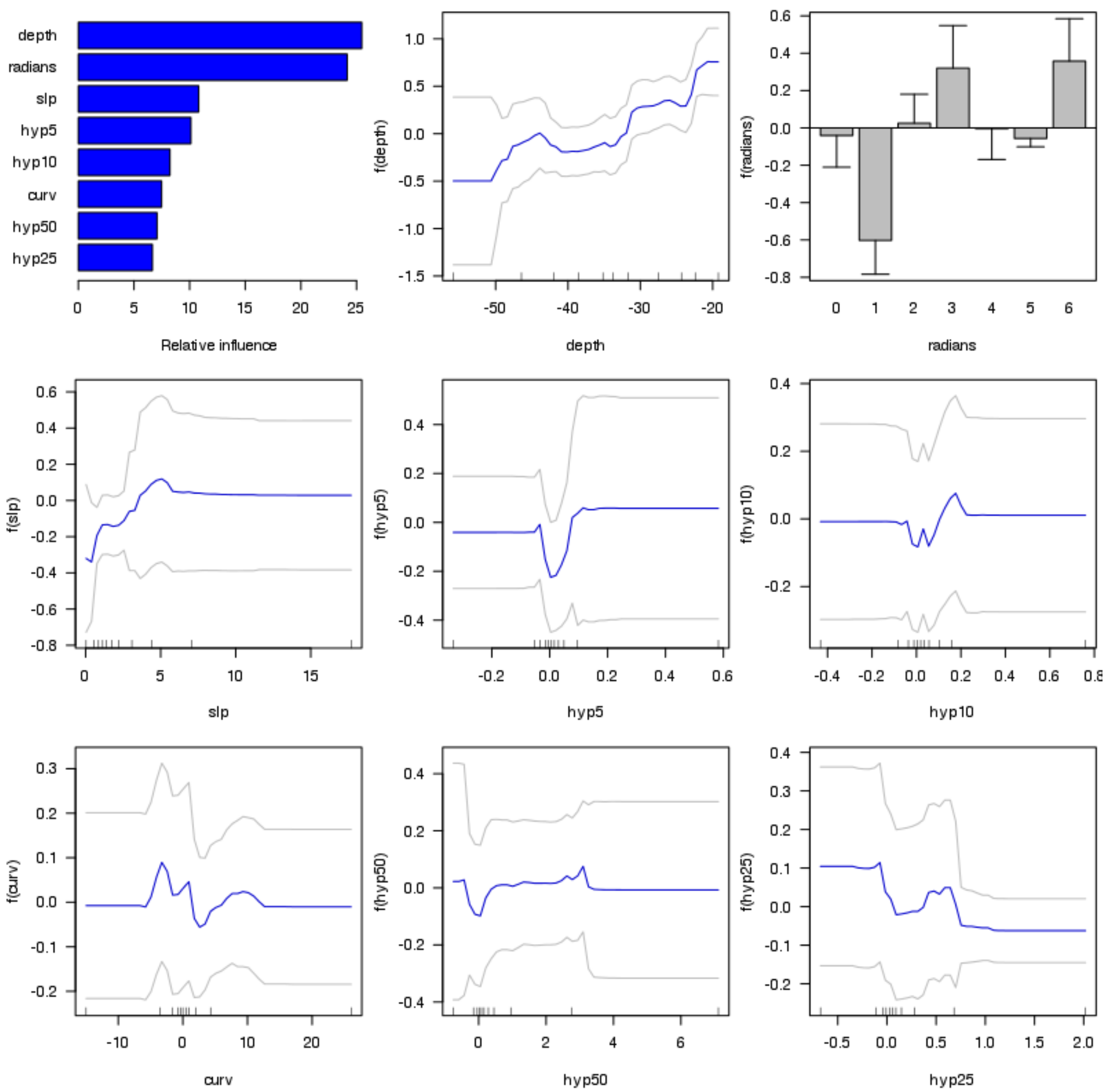


Figure C3.14. BRUVS fish species abundance (total n) partial response plots. Y-axis are mean centered probability of occurrence.

4. Fish community assessment using Baited Remote Underwater Video Stations (BRUVS™)

4.1 Introduction

The uncontrolled release of hydrocarbons into the sea, along with dispersant chemicals used in operational response to spills, has the potential to affect fish communities in a number of ways. For example, through the reduced survival of eggs and larvae exposed to hydrocarbons (Carles et al. 1999; Carles et al. 2000; Incardona et al. 2012), and dispersants (Couillard et al. 2005), reduced survival and growth of recruits, with subsequent population level effects (Heintz et al. 2000), genotoxicity in adults and fin erosion (Theodorakis et al. 2012), effects on skin and gills as indicative of chemical and metabolic stress (Giari et al. 2012), and with a range of biological disorders including neoplasm (Malins and Hodgins 1981) and deleterious effects on vitellogenesis (Nicolas 1999). Dispersants can also further increase oxygen consumption and liver activity (Cohen et al. 2001).

Assessment of the potential impacts on biodiversity following the Montara uncontrolled release, where both hydrocarbons and dispersants were released into the sea, included surveys of the fish communities on the submerged shoals and banks within the exposed area and at various distances from the Montara well head platform. As there was no pre-existing baseline information on shoal-associated fish communities for this area, contrasts were made between banks and shoals of predicted high, medium and low exposure to the spill plume as a "gradient" analysis. Such an assessment is complicated by the fact that fish communities vary with habitat at a range of spatial scales (eg Friedlander and Parrish 1998; Kaiser et al. 1998). Thus the cross-shelf location, size, and varying habitats of the banks and shoals meant that the influence of such natural variation on the fish communities needed to be considered in any assessment of potential hydrocarbon or dispersant effects. To further complicate the understanding of spatial patterns, species-environment relationships tend to be inherently asymmetric and non-linear (Austin 2007). They also tend to show heterogeneous scatter of abundances at points along a gradient – often as a consequence of the fact that other un-measured biotic or abiotic factors are limiting abundances and are interacting with the measured covariates in complex ways (Anderson 2008).

We chose to sample fish communities using non-destructive stereo Baited Remote Underwater Video Stations (BRUVS™) (Cappo et al. 2007b). BRUVS have a number of advantages with respect to obtaining quantitative information on fish communities. BRUVS are easily deployed and cost effective (Langlois et al. 2010). They can also be safely deployed across a broad range of shelf depths, whereas the use of divers to conduct underwater visual census is constrained by depth, is more expensive, and presents additional serious safety risks. Unlike fishing-based methods such as traps and lines, BRUVS are non-destructive and lack gear selectivity associated with fish capture (Cappo et al. 2007b, Harvey et al. 2012). Used in stereo pairs, as is the case here, BRUVS have the major benefit of remarkably accurate and precise estimates of fish length (and hence biomass) (Harvey et al. 2002a; Shortis et al. 2009), as well as estimating relative abundance within a known field of view. The use of bait means that stereo BRUVS also effectively sample taxa that may be under-sampled by divers, such as predatory fishes and sharks, as well as a range of other herbivorous and omnivorous species (Watson et al. 2010). Sampling predatory fishes and sharks is important as these taxa are often of fisheries and conservation interest, as well as enforcing "top down" control of prey communities.

Like all fish sampling methods, stereo BRUVS have biases. Specifically, bait plumes may vary in extent and effectiveness between samples (Priede and Merrett 2006, Harvey et al. 2007) and affect behaviour (Birt et al. 2012, Lowry et al. 2012). Additionally, the measure of abundance is relative, rather than a density expressed per unit area. However, these biases are well understood, and more importantly, consistent such that BRUVS have been effectively used to detect spatial differences among fish

communities at the full range of spatial scales from local (metres) variation amongst microhabitats (Lowry et al. 2012), to contrasts between reefs and shoals (kilometres to 10's of kilometres) (Goetze et al. 2011, Langlois et al. 2011), up to regional mesoscales of entire shelves (Cappo et al. 2007a, Malcolm et al. 2007). Changes in fish communities through time have also been successfully documented using stereo BRUVS (McLean et al. 2011, Watson et al. 2007, Watson et al. 2009). The capacity to detect spatial and temporal variation will be important in assessing the potential impacts of the Montara uncontrolled release. In the first instance, variability in fish community structure as a function of spatial distance from the uncontrolled release and other indices of oil exposure will be determined, with the potential for subsequent monitoring of the same sites through time.

In this "snapshot" study, where all shoals were sampled within a narrow seasonal window between mid-March and mid-April 2011, we aimed to study patterns in the structure of fish communities in relation to a spatial gradient away from the site of the Montara uncontrolled release. Our primary goals, in addition to characterising the fish communities on the shoals, were to assess any visible impacts on species richness, relative abundance, length, biomass, community composition (relative abundance of species), probability of occurrence of common species and presence/absence of seasnakes (as these are air breathers and likely sensitive to surface oil slicks), using the best available indices of exposure to the uncontrolled release.

We used two different statistical approaches to explore the potential relationship between fish community attributes and oil spill exposure indices. Firstly, boosted regression trees assessed the influence of oil exposure concurrently with all other covariate (habitat) variables. The focus of these models is on predicting the fish community attributes using a suite of explanatory variables where the optimal model has lowest prediction error. Secondly we built models in a step-wise fashion which allowed traditional hypothesis-testing and assessment of significance levels at each step. The most parsimonious fish/habitat model was developed and the sequential influence of oil spill indices then evaluated, given the nature of the habitat. Combined, these two techniques provided a broad assessment of the degree to which exposure to the uncontrolled release may have influenced fish communities.

4.2 Methods

4.2.1 Field sampling with stereo Baited Remote Underwater Video Stations (BRUVS™)

Demersal fish communities were surveyed using stereo BRUVS (Cappo et al. 2007b, Harvey et al. 2002a; Watson 2006). Information on the design, measurement and calibration procedures are presented in Harvey and Shortis (1996, 1998). The BRUVS consisted of a galvanised steel frame onto which camera housings, an arm bearing a flashing diode and bait canister, ballast weights, ropes and floats were attached. A flexible bait arm held a plastic mesh bait bag containing one kg of crushed pilchards (*Sardinops sagax neopilchardus*) at a distance of approximately 1.2 m in front of the video housings. BRUVS frames were ballasted according to the prevailing sea-state and current conditions to ensure stability on the seabed. An 8 mm diameter polypropylene rope with surface floats attached enabled the BRUVS to be deployed and later retrieved from the surface with a pot-hauler (Figures 4.1; 4.2). The scope of the rope length was selected to be approximately twice the water depth. Each housing contained a Sony HDR-CX110E 'handycam' video camera fitted with a 0.6 X wide conversion lens. The cameras were set to record at full high definition resolution

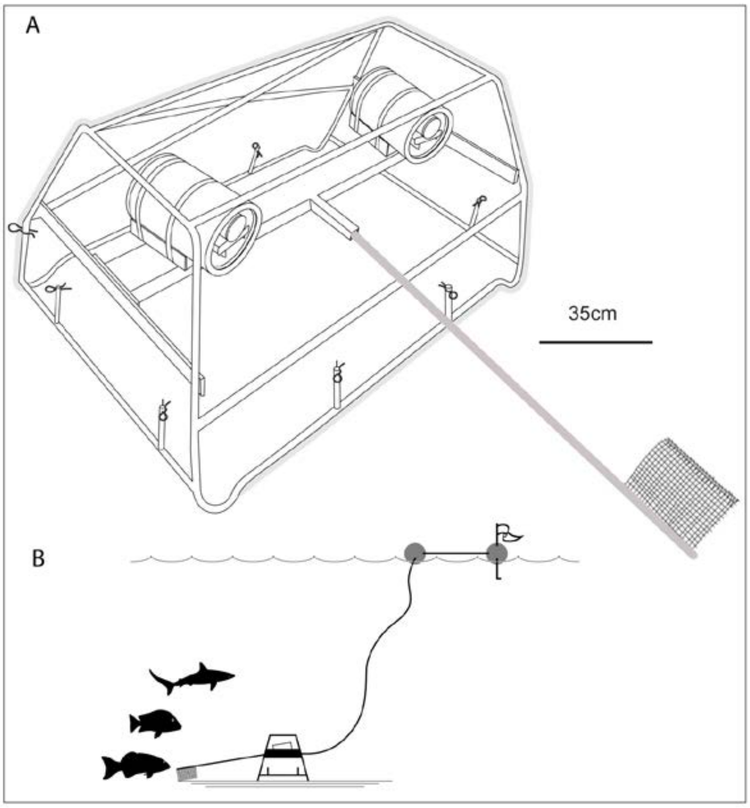


Figure 4.1. A stereo-BRUVS unit with bait arm attached (A) showing typical deployment with bait bag touching the seabed (B).

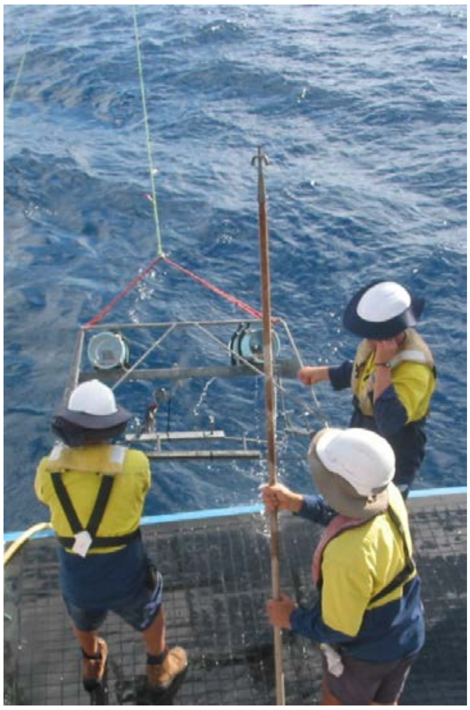


Figure 4.2. Stereo-BRUVS units ready for deployment, and during the process of retrieval.

(1920 x 1080 pixels), with focus set to infinity in manual focus mode. In each camera, footage was recorded for one hour at the seabed on to a 16GB SD card, with recording initiated manually immediately prior to deployment. At the end of each deployment, the footage was downloaded from the cameras via Picture Motion Browser software and stored on portable hard drives in .m2ts file format.

Sampling occurred at nine shoals at varying distances from the uncontrolled release, within the Australian EEZ, which provided a range of nominal exposures based on the modelled spill distribution (see Chapter 1, Figure 1.4). A balanced experimental design would have allocated three shoals to each exposure category (high, medium, low) but as there were only two shoals within the area that fell into each of the high and medium exposure categories, all four of these were thus sampled, with the remaining five shoals falling into the low exposure category. The imbalance in this design directed us towards the use of gradient analyses rather than more classical ANOVA type analysis.

On each shoal, the location of sampling stations was done using a "regular/random" design within the bounds of the 60 m depth contour, whilst maintaining a minimum distance of 250 m between BRUVS. The location, general shape, size and bathymetry of the shoals were determined in advance of BRUVS deployments using multibeam data (Figure 4.3). Once the locations of the sampling stations were established, the sequence of deployments, in sets of eight replicate units, was determined by proximity to the ship's current position and prevailing sea conditions on the day.

Stereo BRUVS were deployed in up to three sets of eight replicates, per day, per shoal, maximising sampling efficiency. The smaller shoals, with 24 or fewer deployments, were sampled in a single day, while larger shoals such as Heywood Shoal required additional days at this deployment rate. Deployments were for at least 60 minutes in order to maximise measures of diversity and relative abundance of aquatic vertebrates (hereafter referred to as fish species). These soak times were based on species accumulation curves derived from a north-western atoll reef fauna (Scott Reef) by Cappo et al. (2001). Adjacent deployments were separated by at least 250 m to avoid overlap of bait plumes and reduce the likelihood of fish moving between deployments within the sampling period (see Cappo et al. 2004 for review).

4.2.2 Data description: fish community, habitat and oil exposure metrics

Three sets of data were required for the analysis. First, fish communities were characterised with respect to the diversity, abundance and size of the species observed at each sampling station. Second, habitat data were generated from a) multibeam swathe mapping, b) the direct field of view of the BRUVS and c) towed video transects, in addition to locational data. Third, exposure to the uncontrolled release was characterised with respect to a) modelled outcomes, b) distance to Montara well head platform and c) sediment hydrocarbon samples. The following sections describe the methods used to generate these data.

Fish community structure – identity, abundance, length and biomass:

In the laboratory, high definition stereo BRUVS footage was converted from .m2ts to .mpeg format using Elecard Converter Studio AVC HD V 3.0. EventMeasure (SeaGIS Pty Ltd 2008) was used to view and analyse footage for measures of relative abundance for all fish species. This software program was purpose built for analysis of fish communities and includes a

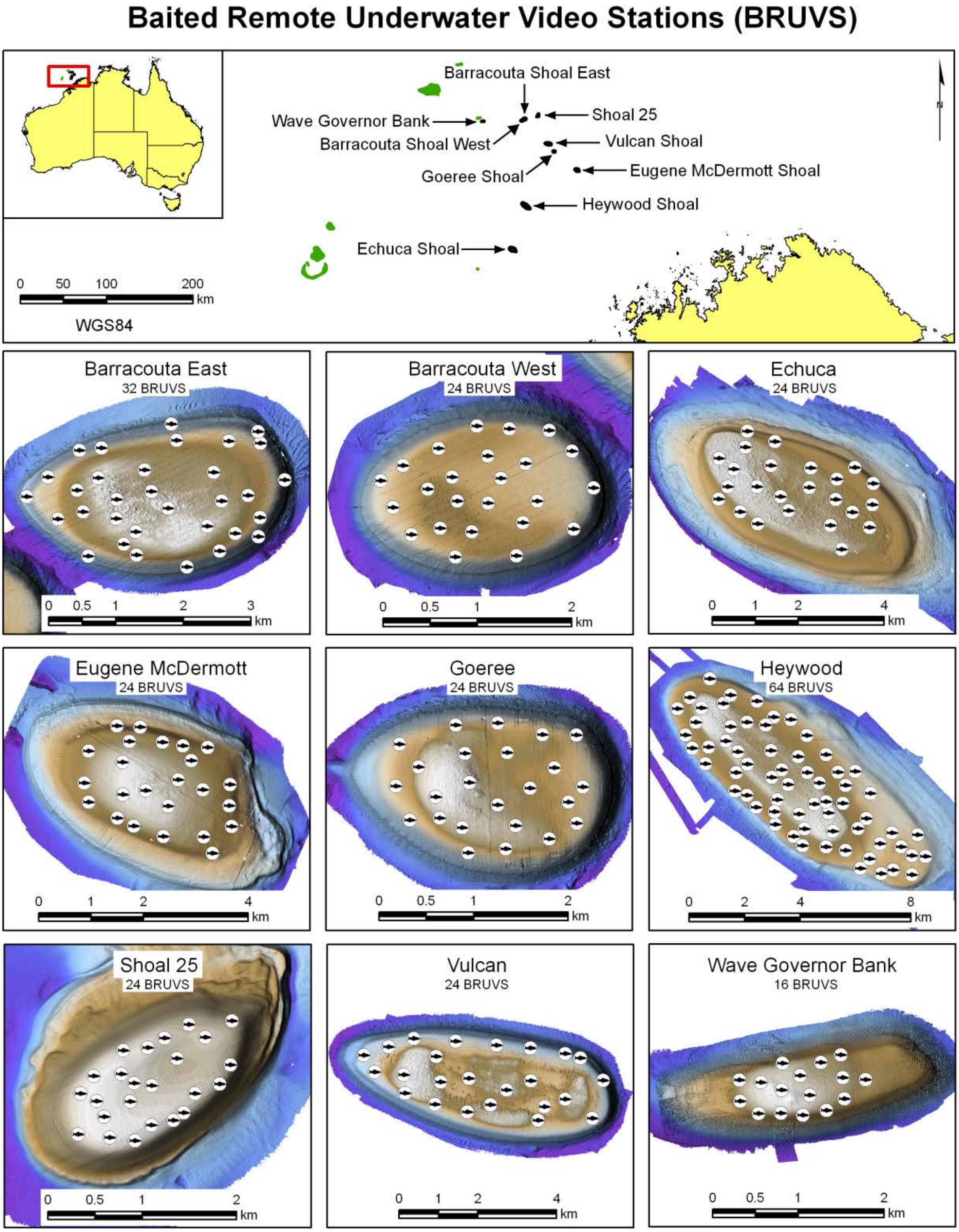


Figure 4.3. Distribution of individual BRUVS deployments overlaid on a planar view 2D map of each shoal, produced from multibeam swath mapping. Depths are shown relative for each shoal, white areas being shallowest, brown intermediate and blue deeper

built-in movie player, extensive fish reference library and the ability to zoom in on targets and mark them.

Commencing immediately after reaching the seafloor, 60 minutes of bottom-time was analysed for all video recordings, regardless of whether video extended longer. Individual fish were identified to the highest taxonomic level possible, aided by high definition video, relevant literature (Randall et al. 1997; Allen et al. 1998; Lieske and Myers 2001; Randall 2002; Allen et al. 2003; Allen 2004) as well as the UWA and AIMS image and video reference libraries. The use of common and scientific names follows the codes and conventions of the Commonwealth codes for Australian aquatic biota (Rees et al. 2011).

Where possible, individuals were identified with their full binomial name, to genus and species. However, where multiple individuals in a known genus could be grouped as a species, but the species name itself was unknown, they were labelled as *Genus* sp1 to *n* where *n* was the total number of unknown but distinctly identifiable taxa in the genus. If a species could be recognised as unique, but not identified to either species or genus, it was labelled as *Family* sp 1 to n. As such, these latter taxonomic groupings represent unique albeit unknown taxa and were counted as species.

Estimates of relative abundance were then obtained as the maximum number of fish belonging to each species present in the field of view of the stereo BRUVS at one very small time period (*MaxN*) (Priede et al. 1994; Cappo et al. 2004). This measure avoids repeated counts of the same individual and provides a conservative measure of relative abundance, as only a portion of the total number of individuals in the area may be viewed at one time. The use of *MaxN* as a conservative estimate of relative abundance has been reviewed extensively (Cappo et al. 2007b; Farnsworth et al. 2007; Willis et al. 2000).

The timing of ancillary events was also collected using EventMeasure such as feeding activity, loss of bait bag, time elapsed to *MaxN* by species, and life stage where visually obvious, as well as estimates of water clarity, or visibility.

PhotoMeasure (SeaGIS Pty Ltd 2008) was used to make length measurements from the left and right stereo pair of images (www.seagis.com.au). To avoid making repeated measurements of the same individuals, measures of length (snout to fork, FL mm) were made at the time of *MaxN* previously determined using EventMeasure. To ensure measurement accuracy and precision, and consistency across samples, all measures of fish length were limited to those individuals within a maximum distance of 8 m from the cameras (Harvey et al. 2002b). At distances greater than 8 m, measurement accuracy can deteriorate. The software calculates both distance from the cameras and length at the same time, allowing measurements of individuals further than 8 m from the cameras to be discarded. Weight of each fish was calculated from a generic length (L)-weight (W) relationship, where $W=aL^b$ with the values for the coefficients a and b calculated as mean values. These mean values were estimated based on those reported for 396 species from 75 familes in Kulbicki et al. (2005). Although a number of species observed in this study were not included in Kulbicki et al. (2005), the variation reported in coefficients across families was sufficiently small, such that mean values across families could be used. Biomass per deployment was then calculated as the number of individuals per species multiplied by the mean weight for that species.

All fish data and still reference images were run through QA/QC procedures prior to being incorporated into the Oracle AIMS BRUVS database via an Access front end. Back-up copies of all imagery and data were also made.

These methods generated a base multivariate dataset on fish community composition including abundance and length for each species. As not all individual fish were measured due to visual occlusion or distance from the camera, missing lengths were interpolated as the mean length of conspecifics observed on same-shoal samples, generating an adjusted mean length for each species at

each sampling station. From this matrix, univariate metrics describing the fish community were estimated for each sampling station such as the total number of species (hence species richness), total abundance of fish, mean length of measured fish and total biomass. Total biomass estimates were based on adjusted mean length to avoid underestimating biomass due to unmeasured but observed fish. Univariate and multivariate attributes of the fish community were calculated at the level of individual sample stations and as mean values for each the nine shoals.

Habitat and locational data

Habitat data consisted of information on the seabed composition, topography and nature of epibenthic plant and animal communities. These quantitative parameters and qualitative estimates were generated from a) multibeam swathe mapping, b) the direct field of the substratum and epibenthos in the view of the BRUVS and c) towed video transects (see Chapter 3 for full description of methods for towed video) (Chapter 3; Table 3.1).

Comprehensive swathe mapping of each shoal by multibeam has been described fully in Chapter 3. Geospatial analysis of the raw multibeam data provided a range of key seafloor characteristics including topography, roughness, hardness, slope, aspect and curvature (Table 3.1). These original parameters were used in their raw form, in association with BRUVS data, to produce shoal-specific maps of fish abundance and species richness. A subset of the parameters listed in Table 3.1 were used directly, or modified, for use in the gradient analysis of responses to signals of the oil plume. These are listed in Table 4.1. For example, the expression of aspect as radians in Table 3.1 was converted to quadrants of a compass in Table 4.1 for ease of interpretation. Locational data were determined for each sampling station and included latitude and longitude as recorded by the vessel's GPS.

Each BRUVS deployment provided a view of the adjacent seabed and thus provides habitat data for that sampling station. For the current study, a standardised classification scheme for the seabed in the BRUVS field of view was developed and applied by reviewing an image of the seafloor from each of the BRUVS sampling stations. To provide quantitative estimates of habitats, the percentage cover (to the nearest 10%) was then determined for six categories of (abiotic) substratum, summed to 100%, and for 13 categories of (biotic) epibenthos, also summed to 100%. Each of the "%cover" variables was measured on the same scale, so no data transformations were made. Some of the categories of substratum or epibenthos were absent, or poorly represented in the dataset in which case, they were pooled with other, larger and related categories to derive the shorter list of covariates.

Table 4.1. Definition of the 41 explanatory covariates used in univariate and multivariate models to examine the relative effect of the uncontrolled release. Covariate types included those estimated in the BRUVS field of view (substratum, epibenthos), those derived using GIS from the multibeam seafloor mapping, and those measured or estimated along a gradient away from the Montara well head platform (MWHP) (oil). Brief definitions of each covariate are given in the right hand column.

Covariate abbreviation		covariate type	Covariate Definition
depth		spatial	Depth (m) measured under the hull when BRUVS deployed
latitude		spatial	BRUVS GPS position
longitude		spatial	BRUVS GPS position
BRUVS field-of-view			
% composition of seafloor by 5 categories of substratum			
visibility		-	Underwater visibility estimated in BRUVS field of view
bldr		substratum	% substratum classified as "boulders"
calc.rf		substratum	% substratum classified as "calcareous reef"
grvl		substratum	% substratum classified as "gravel"
rbbl		substratum	% substratum classified as "rubble"
sndy		substratum	% substratum classified as "sand"
% coverage of 12 categories of epibenthos			
bare		epibenthos	% coverage of seafloor with no epibenthos
encr		epibenthos	% coverage of the seafloor by "encrusting organisms"
fans		epibenthos	% coverage of the seafloor by "fans"
hlmda		epibenthos	% coverage of the seafloor by "*Halimeda*"
hyd		epibenthos	% coverage of the seafloor by "hydroids"
mcralg		epibenthos	% coverage of the seafloor by "macroalgae"
mssv.crl		epibenthos	% coverage of seafloor by "massive corals"
sft.crl		epibenthos	% coverage of seafloor by "soft corals"
sol.crl		epibenthos	% coverage of the seafloor by "solitary corals" (eg fungiids)
spng		epibenthos	% coverage of the seafloor by "sponges"
whps		epibenthos	% coverage of the seafloor by "sea whips"
znthd		epibenthos	% coverage of the seafloor by "zoanthids"
Analysis of multibeam maps			
shoalarea		spatial	Surface area of the entire shoal (hectares)
asp.dir		spatial	Azimuthal direction of the steepest slope, calculated on a 3 x 3 pixel area
curv		spatial	Combined index of profile and plan curvature {concavity/convexity parallel to and perpendicular to the slope), calculated on a 3 x 3 pixel area
hyp5		topography	Hypsometric index - Indicator of whether a cell is a high or low point within the local neighbourhood (kernel pixel radius of 5) original cell size 4m
hyp10		topography	Hypsometric index (kernel pixel radius of 10)
hyp25		topography	Hypsometric index (kernel pixel radius of 25)
hyp50		topography	Hypsometric index (kernel pixel radius of 50)
rng5		topography	Maximum minus the minimum elevation in a local neighbourhood (5 pixels)
rng10		topography	Maximum minus the minimum elevation in a local neighbourhood (10 pixels)
rng25		topography	Maximum minus the minimum elevation in a local neighbourhood (25 pixels)
rng50		topography	Maximum minus the minimum elevation in a local neighbourhood (50 pixels)
std5		topography	Standard deviation of elevation (5 pixels)
std10		topography	Standard deviation of elevation (10 pixels)
std25		topography	Standard deviation of elevation (25 pixels)
std50		topography	Standard deviation of elevation (50 pixels)
slp		topography	First derivative of elevation: Average change in elevation / distance calculated on a 3 x 3 pixel area
Indices of exposure to the Montara uncontrolled release			
newoiladj		oil	Adjusted measurement of hydrocarbons in sediment samples
oilhours		oil	Maximum number of hours of exposure to oil (from "OILMAP" pers comm. Dr B.King)
compass		spatial	Compass direction of site from Montara Montara well head platform
spilldist		spatial	Distance (km) of site from Montara well head platform

Measures of oil exposure

The exposure metrics were calculated from several sources;

(i) A priori classification as “low”, “medium” and “high” exposure based on shoal position relative to the uncontrolled release (Figure 4.4).

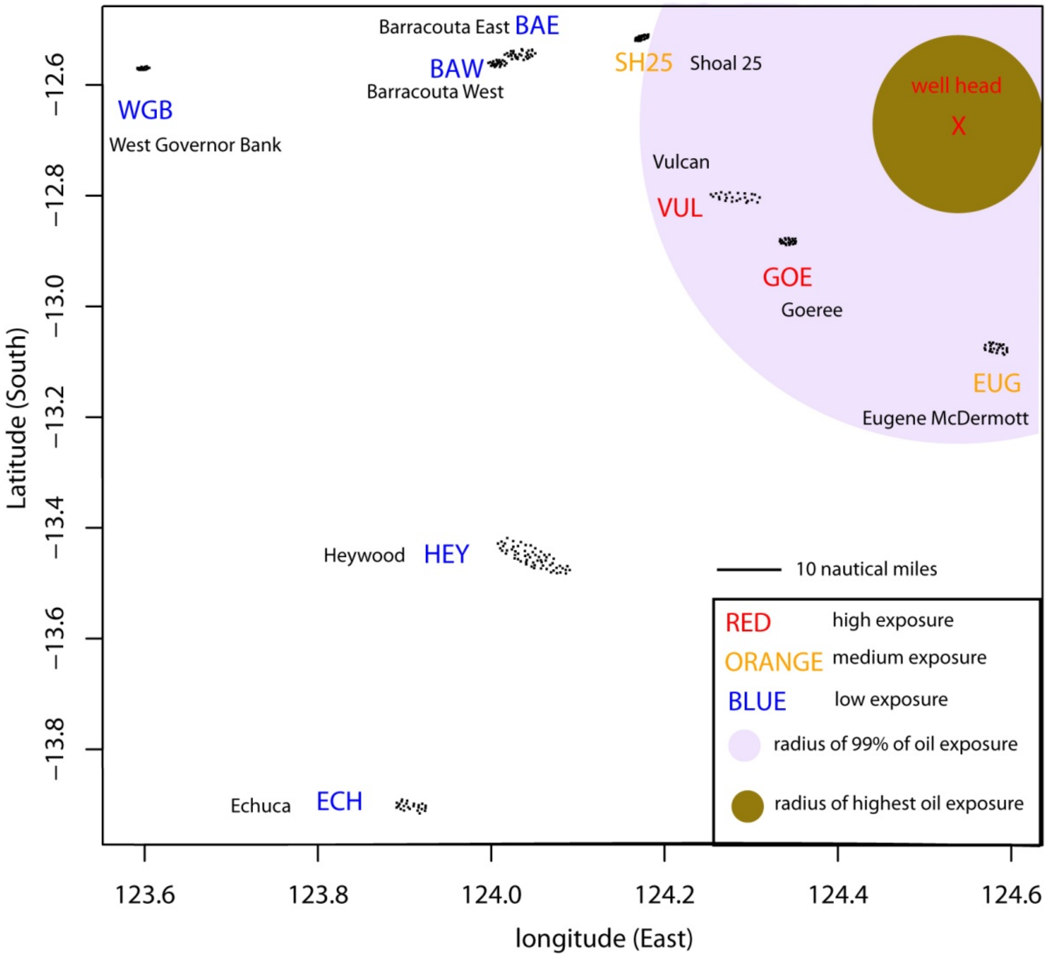


Figure 4.4. Location of BRUVS drops on nine shoals in relation to the MWP. Shoals are coloured by their “exposure category”. Radii reported by King et al. (2010) for distances of maximum exposure (12.3 nautical miles) and 99th percentile (44 nautical miles) are shown as circles. Note that the “true” trajectory modelled by ASA Pacific (2010) was not circular (see also Chapter 1, Figure 1.1).

(ii) Hydrocarbon concentration in the sediments ([HC] as µg/g sediment); samples were collected at four stations to the north, east, south and west of eight of the nine shoals and near the Montara well head platform (see Chapter2). Sediment hydrocarbon concentration was estimated as the mean value of those samples classified as <50% mud (see Chapter 2). Non-detects were estimated as 0.015 µg/g, based on half the detection limit (see Chapter 2). Wave Governor Bank was not sampled due to weather, but given its and categorization as a low exposure site, it was also given a value of 0.015 µg/g. On consideration of the results, the value of 0.57 µg/g at Eugene McDermott shoal was more than double that of Vulcan shoal, closest to the Montara well head platform ([HC]= 0.24 µg/g). This likely reflected the fine sediments at this location, despite our attempt to correct for this by only using the value of the single, relatively coarse sample. We thus estimated the value for Eugene McDermott based on the strong relationship between [HC] and distance from uncontrolled release (r^2=0.83; Figure 4.5.).

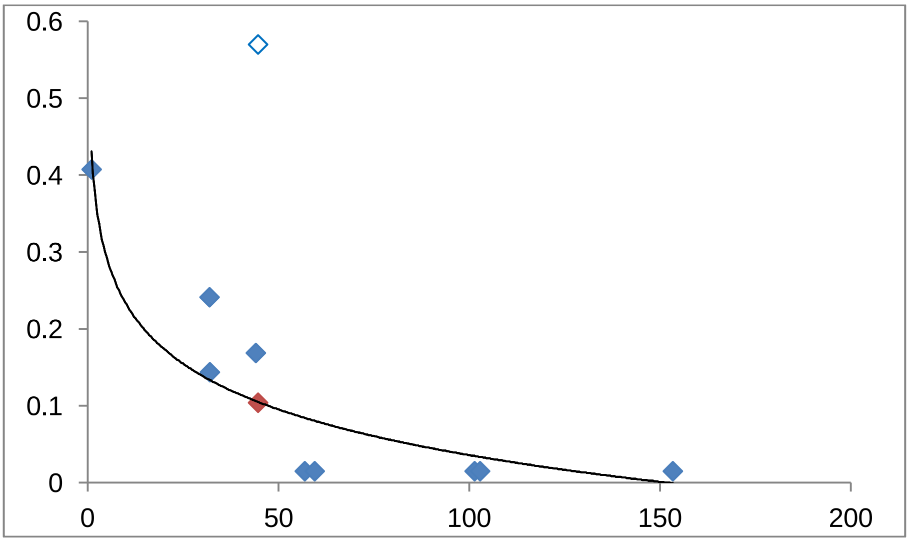


Figure 4.5. Least squares regression of HC concentration (µg/g) vs distance from the Montara well head platform for all points, excluding EUG (open point). The adjusted EUG value (red diamond) is predicted based on the regression equation: [HC] = -0.086ln(distance+1)+0.4307 ($r2=0.83$, $p=0.0006$).

(iii) Minimum and maximum hours of exposure to the surface oil plume based on data provided by ASA Asia Pacific (ASA 2010b). The occurrence maps represent the number of hours of exposure per 1.1 km x 1.1 km cell. We overlaid the BRUVS locations over the corresponding 1.1km x 1.1km grid cells and added the attribute PNTPOLYCNT (Minimum - maximum exposure) to our BRUVS location data as follows, noting that exposure is balanced by degree of surface coverage as well as time of exposure:

a) 0.01% occurrences was roughly 1-2 hours duration (PNTPOLYCNT = 2)
b) 0.1% occurrences was 10-20 hours duration (PNTPOLYCNT = 20)
c) 1% occurrence was 100-200 hours duration (PNTPOLYCNT = 200
d) 10% occurrence - 100% occurrence (PNTPOLYCNT > 200).

(iv). Distance (km) and compass bearing (degrees) from uncontrolled release. ArcGIS was used to measure both bearing and distance from the BRUVS locations to the charted location of the MWHP. An ESRI shape file was projected to WGS84 UTM Zone 51S and arcs between the BRUVS drops and the MWHP were digitised. The bearing and distance tool was used to populate the attribute table.

The location of shoals in terms of their latitude and longitude defines their position on the shelf but also with respect to the uncontrolled release. To this end, these variables are also proxies of exposure, particularly given they only represent approximately 33% of the compass (174° to 294°) and are largely downstream of the modeled spill (see Chapter 1; Figure 1.4). This confounding of position on the shelf and exposure presents interpretation challenges with respect to disentangling cross-shelf and latitudinal patterns from those associated with exposure to hydrocarbons.

4.2.3 Statistical analyses

Fish community data are often characterised by complex patterns for species in relation to where they occur and their densities as a function of numerous environmental variables. Consequently, we adopted multiple statistical approaches to explore this dataset, characterise patterns observed on each shoal and investigate evidence using all data for effects from the uncontrolled release. There were four key types of complementary analysis based on regression trees, general additive mixed models (GAMMS) and linear regression models. These approaches were applied to univariate community attributes such as species richness, total fish abundance, and species presence/absence (occurrence), and to multivariate species abundances.

Characterising spatial patterns of fish diversity and abundance within shoals using multibeam parameters.

Modelling approaches are as described for benthos in Chapter 3. Results here include outcomes also using the BRUVS fish data. Maps of fish diversity and abundance on each shoal were produced using BRUVS data plus multibeam depths and covariates (rugosity etc) see Table 3.1 (topographic or spatial covariates as predictors). The response plots show each covariate and how fish abundance or biomass respond. The first family of analyses were done separately for each shoal, using only multibeam explanatory variables (see Table 3.1) to produce maps at very fine spatial scales of the best fitting estimates of total species richness and total fish abundance within a shoal.

To infer spatial distributions of (a) marine biota, (b) abiotic substrate and (c) fish abundance and species richness, we characterised environmental relationships in detail using the combination of towed video footage, BRUVS fish counts, multibeam hydroacoustic surveys combined with a statistical modelling approach. Towed video and BRUVS observations provide the basic information quantifying what was found on the benthos, while bathymetry and textural datasets provide information on environmental characteristics, and give full coverage of the field area.

To model the relationships between fish abundance, species richness and habitat, we trialled three contemporary methods using subset of models, including random forests, Boosted Regression Trees (BRTs), and a derived method, Aggregated Boosted Trees (ABT's). All are well suited to dealing with complex ecological datasets that contain correlated predictor variables and display non-linear relationships. Although all methods performed well and 'random forests' was considerably less time consuming to run, BRTs and ABTs consistently provided more accurate models. All final models used multivariate regression and prediction trees (De'ath et al. 2007) because they:

(a) provided estimates of standard errors with fits
(b) have been documented to perform well with smaller datasets
(c) were consistent with other methods used in modelling BRUVS data.

A detailed description of the application of this method with ecological data is outlined by De'ath (2007). The final model was constructed using a maximum of 5000 trees, three levels of interaction and five-fold cross validation. This ensured that the model was representative of the area as a whole, and was not biased toward any particular subset of data. Plots of model responses with standard error are shown in Figures A4.2.1, A4.2.2 and Chapter 3: Appendix 3C. Model accuracy statistics are shown in Chapter 3, Table 3.4. The R library `abt` was used for tree construction of models and graphics (De'ath 2007).

In the case of towed video benthic analysis (see Chapter 3 for methods), the ABTs were evaluated using a subset of the video observations reserved prior to modelling (~20% of the full dataset selected via variogram so as to be largely spatially independent from the training data). The model accuracy was assessed by predicting the values against this blind validation dataset using receiver-

operator characteristics (ROC) analysis. ROC are visualised as plots of model sensitivity (classification accuracy) versus specificity (false positive rate). The larger the area under the curve (AUC), the more robust the model for prediction. Models with AUC greater than 0.8 have high predictive power, values between 0.7 and 0.8 are acceptable and models with AUC of 0.5 or less have no power of discrimination (Hosmer and Lemeshow 2000, Manel et al 2001). For the fish abundance and biomass analysis, ABT model performance was assessed by residual deviance and cross-validated correlation. Finally spatial maps showing probability of occurance (values ranging between 0.0 to 1.0) were produced.

Relationships between species richness, abundance and occurrence as a function of habitat and indices of oil exposure

The first analysis assessing the influence of the uncontrolled release on fish assemblages used boosted regression analyses. Boosted regression analyses were introduced to the ecological literature only recently by De'ath (2002; 2007). This approach derives from both classification and regression trees starting with a data model (De'ath & Fabricius 2000) and from 'machine learning' where no data model is specified and algorithms are used to learn the relationship between a predictor and its response (Breiman 2001). Boosted regression trees are therefore an 'ensemble' method, whereby models are improved by first fitting many simple models and then combining them for prediction, using an algorithm from classification and a 'boosting' algorithm, which combines a collection of models (Leathwick et al. 2006, Elith et al. 2008).

Table 4.2: Desciption of shoals including the abbreviations used in figures (Abbrev.), the number of BRUVS samples per shoal (n), the linear distance and compass bearing from the uncontrolled release (spilldist), the sediment hydrocarbon concentration [HC] with number of sediment samples in (), the minimum and maximum hours of modelled exposure (minHRS, maxHRS), the area of the shoal above 60 metres depth and the mean, minimum and maximum depths of BRUVS samples.

Shoal	Abbrev.	n	mean latitude	mean longitude	exposure category	spilldist (km)	bearing (°)	[HC] µg/g	min HRS	max HRS	area (ha)	mean depth (m)	min depth (m)	max depth (m)
Barracuda East	BAE	24	-12.545	124.0336	Low	56.56	284.47	0.015 (4)	12.5	25.0	602.5	26.8	18.6	44.4
Barracuda West	BAW	24	-12.561	124.0067	Low	59.07	281.98	0.015 (4)	8.1	16.2	301.6	33.5	26.3	47.0
Echuca	ECH	24	-13.902	123.9071	Low	153.21	206.37	0.015 (4)	0.2	0.3	1266.0	26.1	19.2	40.4
Eugene McDermott	EUG	24	-13.075	124.5828	Medium	44.99	174.40	0.104† (1)	48.5	97.0	613.2	37.5	20.4	60.8
Goeree	GOE	24	-12.882	124.3427	High	31.65	222.33	0.144 (4)	424.3	848.5	319.6	35.5	25.0	46.4
Heywood	HEY	64	-13.453	124.0474	Low	101.78	211.62	0.015 (4)	3.1	6.2	3537.0	33.3	18.3	49.8
Shoal 25	SH25	24	-12.515	124.1733	Medium	43.43	293.72	0.169 (4)	23.0	46.0	217.1	36.1	31.4	44.3
Vulcan	VUL	24	-12.802	124.2816	High	31.42	242.42	0.241 (4)	472.6	945.3	1299.0	29.7	20.4	46.2
Wave Governor Bank	WGB	16	-12.570	123.5983	Low	102.79	276.26	0.015‡ (0)	0.0	0.0	131.7	44.6	38.4	49.7

† This value, at 0.57 µg/g , was higher than that of the most exposed shoals (GOE and VUL) and likely reflects the relatively silty nature of the area; as such it was recalculated based on the relationship between [HC] and distance (see Results, Figure 4.5).
‡ Not measured but assigned based on location.

Aggregated Boosted regression trees are a recent extension of this approach, but can be summarised in ways that give powerful ecological insight by representing complex information in a visual way that is easily interpretable. They are robust and flexible, because explanatory (predictor) variables can be numeric, categorical, binary, or of any other type, and model outcomes are unaffected by transformations and different scales of measurement of the predictors. They are not sensitive to outliers and handle missing data in predictors by applying best surrogates with little loss of information. Trees are hierarchical structures, and input variables at the tree levels are dependent on input variables at higher nodes. This allows simple modelling of complex, non-linear interactions that simply cannot be handled by other approaches (see examples in De'ath 2007).

A mixture of 41 explanatory covariates relating to spatial position, exposure to oil, substratum, epibenthos and shoal topography (see Table 4.1) was used to explain and predict univariate responses using aggregated boosted regression trees (ABT; De'ath 2007, Ridgeway 2007).

The responses were:

- species richness (raw total number of species on 248 BRUVS drops),
- total fish abundance ($\Sigma MaxN$; 4th root transformed)
- the presence/absence (occurrence) of the 54 most prevalent fish species occurring at 40 or more BRUVS sites (~15%)

The models all allowed for an interaction depth of three, and the results show the relative influence of all 41 covariates (including distance from the uncontrolled release, hydrocarbons in sediments, and maximum hours of oil exposure). They are best portrayed as partial dependency plots, which show the effect of one particular covariate with the effects of all others held constant. Interactions are often non-linear and can be viewed with three-way partial plots.

Identifying and mapping fish community assemblages using environmental covariates and indices of oil exposure.

The regression tree approach can be extended further by replacing the univariate response with a multivariate response, such as the abundances of a large number of species at each site (see De'ath 2002). Each split in the tree minimises the "distance" of sites from the centroids of nodes to which they belong. This is equivalent to maximising the distance between node centroids. Each terminal node of the tree (leaf) can be defined by the multivariate mean of its sites, the predictors that define it, the number of sites that were grouped there, and by Dufrêne -Legendre species indicators (DLI; Dufrêne and Legendre 1997).

The DLI values were calculated for each species for each upper (branch) and terminal (leaf) node of the tree. For a given species and a given group of sites, the DLI is defined as the product of the mean species abundance occurring in the group divided by the sum of the mean abundances in all other groups (specificity), times the proportion of sites within the group where the species occurs (fidelity), multiplied by 100. Each species can be associated with the tree node (assemblage) where its maximum DLI value occurred. The index distinguishes between ubiquitous species that dominate many groups in absolute abundance, and species that occur consistently within single groups but have low abundance (Dufrêne and Legendre 1997). The DLI for species at the root node are simply the prevalence of those species in the entire dataset. Species with high DLI can be used as characteristic representatives of each community. The spatial extent of the fish assemblages identified by the tree leaves were mapped for each shoal by assigning each BRUVS site to its membership of an assemblage.

All analyses incorporating regression trees used the open-source R statistical package (R.Development.Core.Team 2006). We used the public libraries `mvpart`, `vegan`, and `abt` (Ridgeway 2007), and another in the Ecology Archives (`gbmplus`; De'ath 2007, http://www.esapubs.org/Archive/ecol/E088/015/suppl-1.htm). Private libraries (`treeDLI`, `DLI`, `geoPlot` and `geo`) were supplied for our use by Dr Glenn De'ath (AIMS).

General additive mixed models (GAMMs) and linear regression to predict univariate fish community responses to the uncontrolled release

The second analytical approach used a combination of general additive mixed models (GAMMs) and linear regression to test for potential effects of the uncontrolled release on fish community structure controlling for habitat variability. To do this, three key decisions were taken in the analysis of the potential impacts:

(i) Classic environmental impact studies compare reference sites to impact sites before and after the event of interest (Underwood 1982; Green 1979). Such analyses benefit from multiple control and impact sites and are most powerful when the designs are balanced (i.e. an equal number of control and impact sites). In this study, in addition to having no before data, we were limited by the number of shoals available for sampling and these were unequal in their distribution across exposure levels (Table 4.2). Moreover, as the shoals reflected a gradient of exposure with respect to distance from spill and hours of exposure, we chose a design to test for effects along a continuum of exposure rather than *a priori* categories of exposure, reflecting the greater potential of techniques based on continuous data to detect change (deBruyn and Meeuwig 2001).

(ii) A two part analysis was taken to evaluate the potential impact of hydrocarbon exposure on fish communities. Habitat profoundly determines the composition and structure of fish communities (c.f. Friedlander and Parrish 1998, Friedlander et al. 2010). For example, species richness and total abundance often increase with habitat complexity and the type of habitat determines which species are present and their relative abundance. The nine shoals sampled in this study varied significantly in their habitat (Chapter 3; Heyward et al. 2010) thus it was not possible to simply contrast fish communities across exposures. Fish responses to exposure must thus be assessed in light of the habitat. To this end, statistical analyses consisted of a) identifying the "best" relationship between fish and habitats and b) then including exposure metrics in the model to determine whether exposure further explained the observed variation in the fish communities and whether the direction of this impact was consistent with ecological predications. Significance testing was relaxed to $p<0.10$ in order to mitigate the risk of failing to detect an effect of exposure that is present (Type II Error, or an error of excessive scepticism).

(iii) A hierarchical approach was taken to sampling whereby BRUVS were deployed in a nested fashion across the nine shoals. Fish communities will likely vary within shoals due to small scale habitat variability and across shoals due to shoal level variability (size, latitude and longitude) (see for instance MacNeil et al. 2009) as well as potentially due to exposure to hydrocarbons and dispersants. The small number of available shoals (n=9) made analyses at the level of shoal challenging but the inherent variability between deployments renders the data relatively noisy. To this end, fish, habitat and exposure relationships were explored at the level of deployment and at the level of shoal, with appropriate caveats provided.

Testing the effect of exposure on fish community structure was completed as follows. Permutational ANOVA (Anderson 2001) was used to test for basic differences in univariate

metrics of fish community structure as a function of shoal. Fish habitat models were then developed, using only one set of habitat variables at a time (i.e. data derived from either multibeam or BRUVS or towed video) given the likely correlation between these datasets. The following univariate fish community attributes were calculated for each deployment (n=248): the number of species (hence species richness, SR), total abundance (TA), mean fork length (FL), and total biomass (B), based on adjusted mean lengths. Generalized additive mixed models (GAMMs) were used to document the strongest relationships between univariate fish community attributes and habitat variables (Pinheiro and Bates 2000, Zuur et al. 2009). GAMMS extends the generalized additive model (GAM) to include random effects to account for correlation among observations on the same sampling unit (here shoal). For each model, the fixed components (covariates that are not influenced by the hierarchical structure in the data) were the habitat variables and oil exposure metrics. The fixed components or predictor variables could be either linear or non-linear, therefore, GAMMs were applied because these models can accommodate both types of variables.

The random effects component of the model accounts for the spatial variation within and between shoals and explains the hierarchical structure of the data. Observations within each shoal shared the same spatial variability and were regarded as not independent. Here two models were tested: 1) random effect on the variable "shoal"; 2) spatial correlation structure on latitude and longitude. For the spatial correlation structure, several spatial correlations were tested including exponential, Gaussian, linear and spherical spatial correlation. Several models were developed for each measure, including linear regression, linear mixed-effects models and generalized additive models. Various measures of goodness of fit were applied to identify the 'best' model, these measures included adjusted R^2 (adjR^2), Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC) and the (restricted) log-likelihood test. For all fish community attributes, the best model, i.e. model with highest adjR^2 and lowest AIC and BIC was the model that included the random effect on the variable "shoal". All models were analysed using the R (R Development Core Team 2007) function `gamm`.

On determination of the strongest fish habitat model, exposure metrics were then introduced and tested within the GAMM to determine whether they significantly explained variation in the fish community, having controlled for habitat, i.e. increase in R^2 and decrease in AIC and BIC (Pinheiro and Bates 2000, Zuur et al. 2009).

Given the high variability between samples within shoals, we also applied linear regression (Zar 1999) to the mean values of fish attributes by shoal to first, establish patterns between fish attributes and habitat variables, then to assess the influence of the exposure values. Caution is required in applying this approach given the small sample size (n=9) and potential for non-linearity in some variables. To address the former, only a single habitat variable was used in each model to avoid overfitting the data. Non-linearity was evaluated by careful assessment of the residuals. To provide a sense of the within-shoal variability, plots include error bars.

Where there was a significant effect of exposure for either the GAMMs or the linear regressions, the size of this effect was calculated as the percent difference between the expected value as a function of habitat and exposure and that expected as a function of habitat alone, relative to the expected value from habitat alone:

$$ES = \frac{(DV_{H+E} - DV_{H+N})}{DV_{H+N}}$$

where ES is the effect size, DV is the dependent variable of interest (i.e. species richness), DV_{H+E} is the predicted value of the DV based on habitat (H) and exposure (E) and DV_{H+N} is the

predicted value of the DV based on habitat (H) and a no-exposure (N) value. For the different exposure metrics, the "no-exposure" value was set as follows: distance from uncontrolled release as the mean distance for the five "low" exposure shoals (96 km); minimum hours of exposure = 0; and hydrocarbon concentration = 0.015 (the non-detect value). These values were predicted from either GAMMs or the linear regression models that included both the habitat and exposure variables.

Modelling sea snake occurrence and abundance in relation to indices of the uncontrolled release

As air-breathing vertebrates that dive to feed on the seafloor, the sea snakes were considered to be especially vulnerable to the effects of the uncontrolled release and the use of dispersant throughout the entire water column. Thus we included some specific analyses of their occurrence and abundance in our study. The distribution of sea snakes relative to habitat and exposure was modelled similarly to the univariate metrics of fish communities at the level of individual deployments and the shoals using both regression trees and logistic regressions. The regression tree approaches used all 41 explanatory covariates simultaneously to identify which covariates were most influential in predicting the occurrence of seasnakes, and their membership of assemblages. At the deployment level, logistic regression was used to model presence / absence of sea snakes relative to habitat and then habitat and exposure. This analysis was selected as more than one sea snake was observed on only 7% of the deployments. At the shoal level, linear regression related the mean number of sea snakes observed per deployment by habitat and exposure.

4.3 Results

A total of 248 BRUVS deployments from all nine shoals were analysed (Figure 4.3). The BRUVS were effective in capturing a significant measure of fish diversity and abundance with 338 species of fishes, sharks, rays and sea snakes recorded. The number of species recorded was a function of sampling effort, regardless of shoal size or depth such that if more sampling had been done, further fish species would have been recorded (Figure 4.6). Consequently, there remains an additional, undescribed or latent component of fish diversity on the shoals. Nonetheless, the 338 species found in this study represent a major subset of the total fish diversity present, including significant numbers of species of fisheries and conservation interest (Appendix 4.1). The proportion of the total species pool recorded per shoal ranged from 28.1% (Wave Governor Bank) to 63.3% (Heywood), with the average proportion of the species pool present on any given shoal being 45.9% or having an approximately one in two chance of being observed. In terms of abundance, more than 25,000 individuals were identified from the BRUVS imagery, of which >97% were teleosts. The remaining 3% consisted largely of 590 sharks and rays and 117 sea snakes (see Appendix 4.1). Lengths were measured for 12,258 individuals and ranged from a 14 cm neon damselfish (*Pomacentrus coelestis*) to a 2.6 m lemon shark (*Negaprion acutidens*).

The shoals varied in size over an approximate order of magnitude from 132 ha (Wave Governor Bank) to 3,537 ha (Heywood) (Table 4.2). The mean depth at which BRUVS were deployed ranged from 26.1m to 44.6 m. Habitat abundance and distribution varied by shoal, from low biotic cover (i.e. Vulcan) to high biotic cover (Eugene McDermott) (see Chapter 3 for details).

The nine shoals varied in their exposure to the uncontrolled release. *A priori*, two were classified as high exposure (Vulcan and Goeree), two were classified as medium exposure (Eugene McDermott and Shoal 25), with the remaining shoals classified as low exposure (Table 4.2). Their distance from the uncontrolled release ranged from 31.4 km to 153.2 km, with sediment hydrocarbon concentrations ranging from the non-detect level of 0.015 to 0.24μg/g. However, it

should be noted that various types of hydrocarbons were found in the region and while sediment hydrocarbons sampled near each shoal did show a steady decline with distance from the Montara Well Head, definitive typing of the oil and hence direct attribution to Montara was not possible due to its degraded nature. Consequenlty, while we have used sediment hydrocarbons near shoals as one spatial metric of exposure to hydrocarbons, the relationship to the Montara release is technically equivocal (see Ch 2). Maximum hours of exposure ranged from 0.3 to 945 hrs, with these metrics largely consistent with the *a priori* classification (Table 4.2). This exposure gradient coincided with an east-west longitudinal gradient (cross-shelf) and a latitudinal, long-shore gradient.

4.3.1 Characterising spatial patterns of diversity and abundance within shoals using multibeam parameters.

Patterns of fish species richness and abundance were elaborated, using multibeam, BRUVS and habitat data, to produce spatial models for each shoal. Model performance was good for fish diversity (cross-validated correlation of 0.70) and poorer for fish abundance (cross-validated correlation of 0.43). Both diversity and abundance were most highly influenced by depth and aspect. Rugosity variables seemed to have some influence on fish models but these were at a more localized scale (i.e. with rugosity variables hyp5 and hyp10).

Responses to environmental correlates for both fish abundance and species richness had comparable patterns. Species richness (Appendix 4.2, Figure 4.2.1) decreased with depth and was higher at the northern and most southern quadrants of shoals. To a lesser extent, species richness also increased with increasing landscape curvature and increasing slope. Similarly, numbers of fish (Appendix 4.2 Figure A4.2.2) decreased with depth and increased at the most northern and southern aspects of a shoal. To a lesser degree, the abundance of fishes increased with greater slope and higher levels of fine-scale (hyp5) rugosity.

The model outputs, displayed as maps for each shoal plateau (Figures 4.7-4.15), generally showed that species richness is greatest on the shallow shoals, being reduced on Shoal 25 and Wave Governor Bank. Higher species richness is typically associated with the shallowest areas of the shoal plateau. This is also often an area of consolidated complex habitat, where corals are common (see Chapter 3). Fish abundance tended to mirror species richness, but the association with the shallow, species-rich areas was variable among shoals. In addition, there was a consistent region of high abundance of fishes around shoal edges.

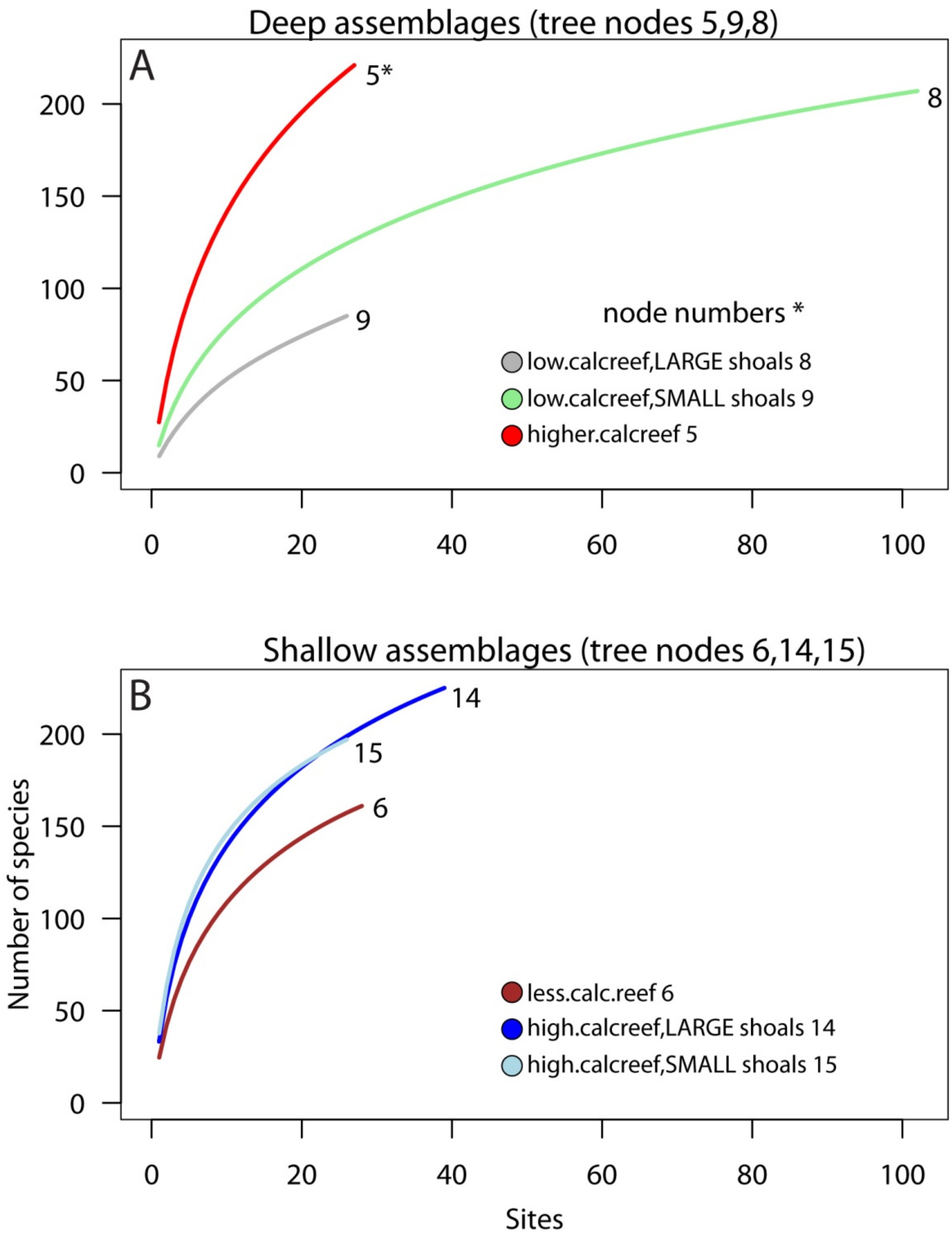


Figure 4.6. Species accumulation curves derived for the six assemblages identified in Figure 4.21. The numbers and node names are shown, and the deep and shallow assemblages are on separate panels. In general the curves were still ascending toward an asymptote, indicating that there remained much latent fish diversity in the assemblages. The curves were steeper for the assemblages characterising sites with higher reefal composition of the substrata.

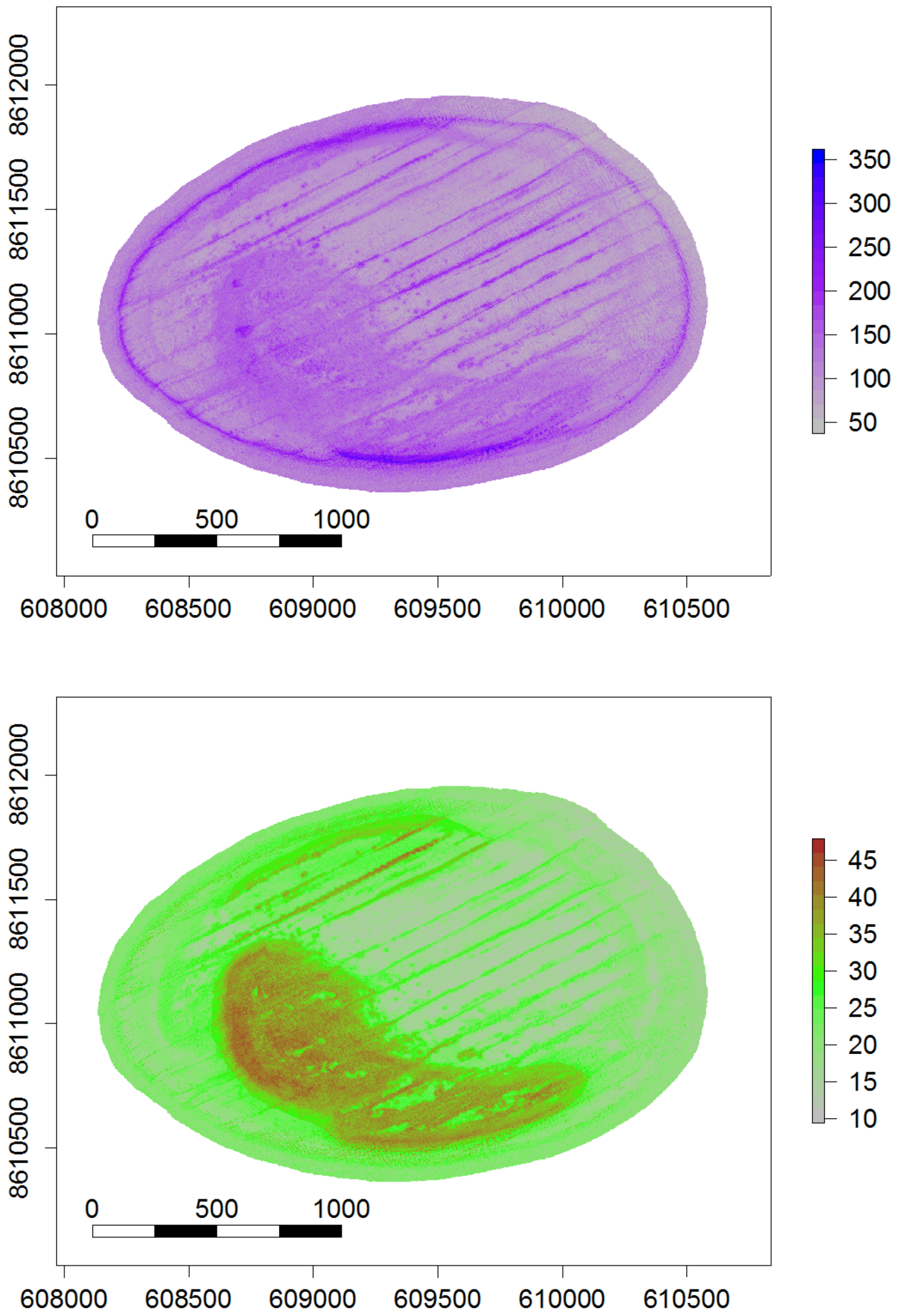
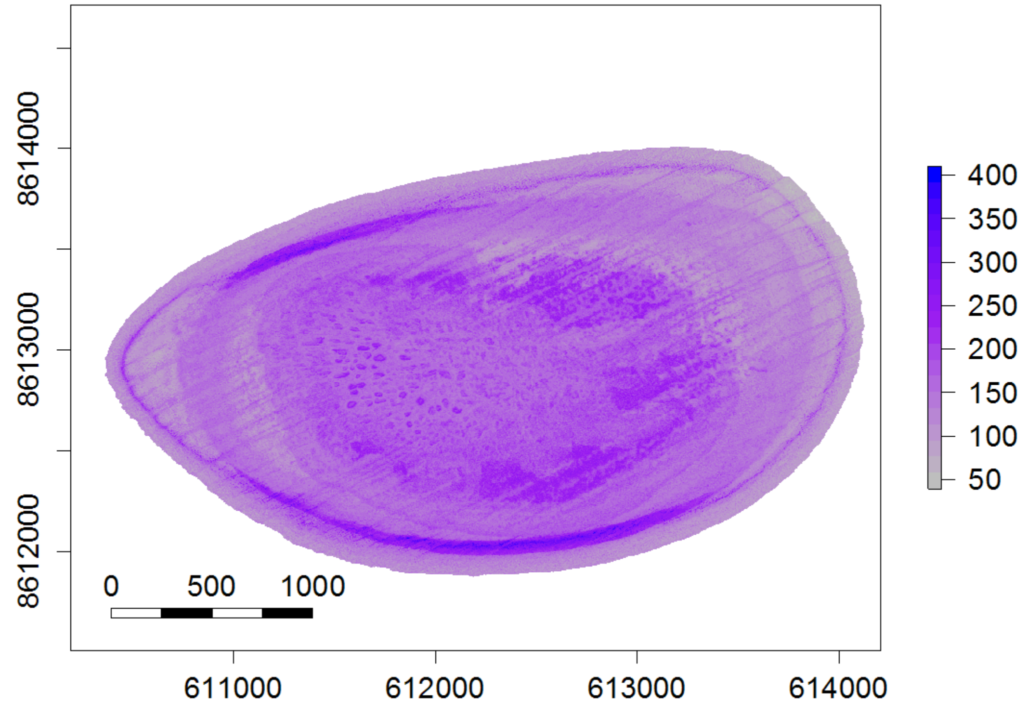


Figure 4.7. Barracouta West BRUVS fish modelled abundance (top, total n) and richness (bottom, number of species). The repeated line edge pattern, creating diagonal stripe marks in this map, is attributable to multibeam sampling artifacts at swath transect overlap zones influencing model outputs



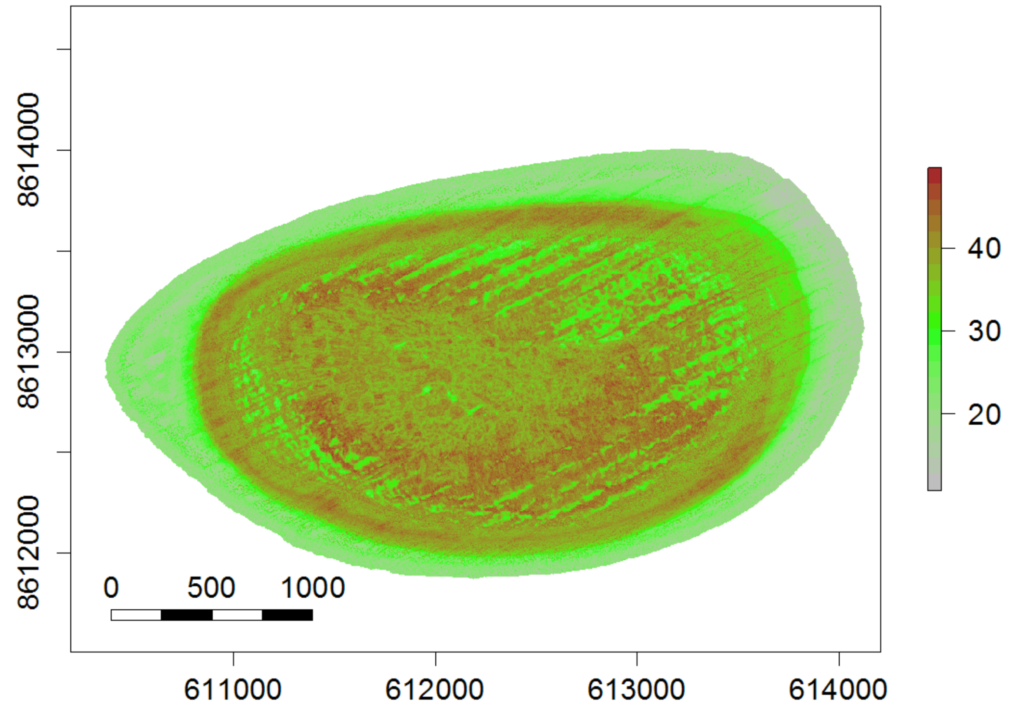


Figure 4.8. Barracouta East BRUVS fish model abundance (top, total n) and richness (bottom, number of species). The repeated line edge pattern, creating diagonal stripe marks, is attributable to multibeam sampling artifacts at swath transect overlap zones influencing model outputs

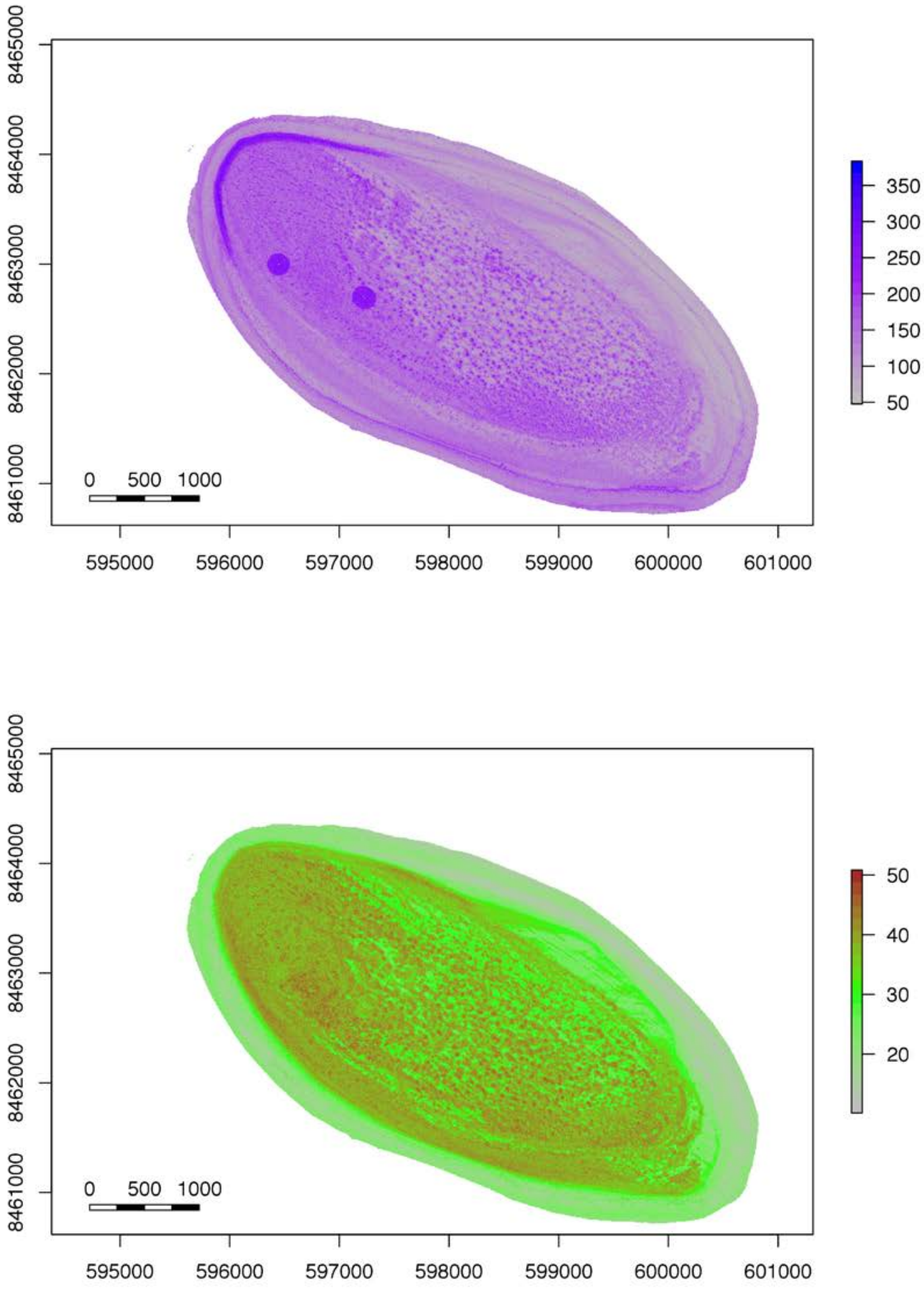
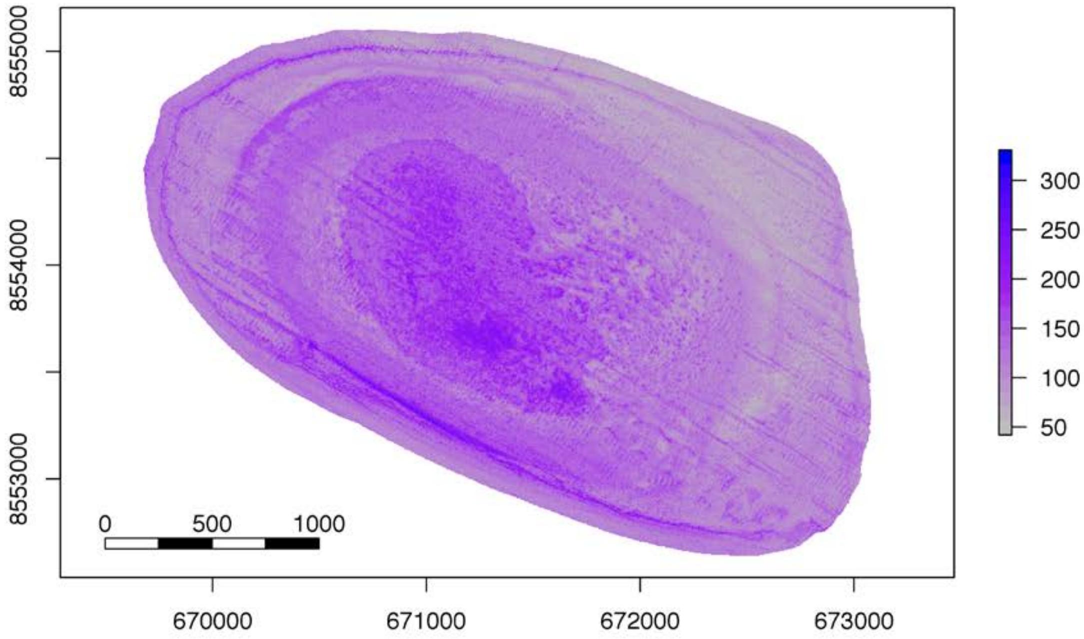


Figure 4.9. Echuca shoal BRUVS fish modelled abundance (top total n) and richness (bottom, number of species).



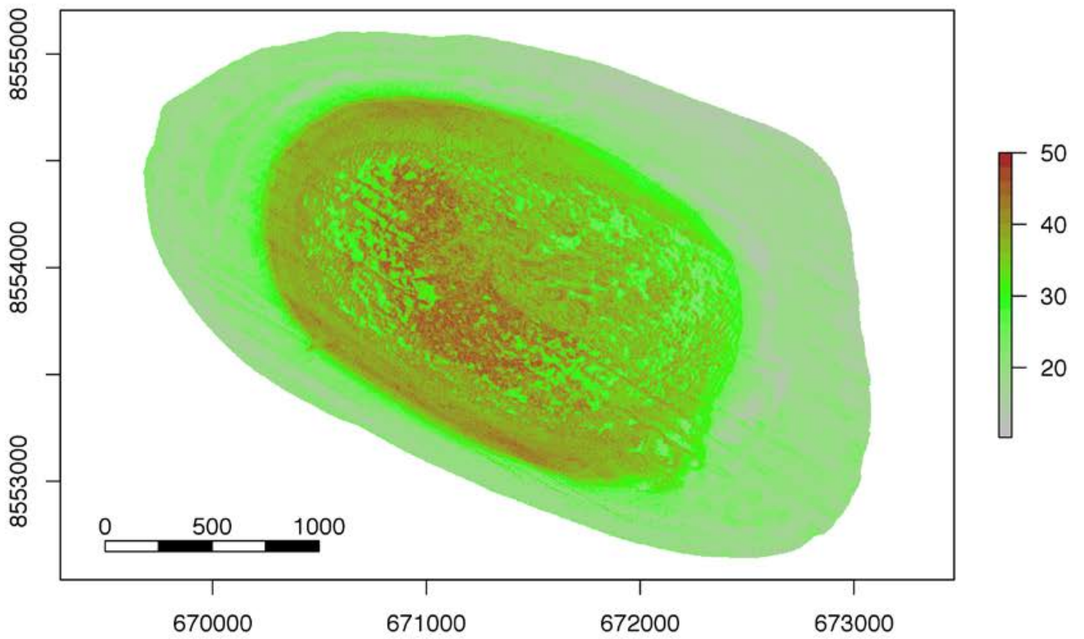


Figure 4.10. Eugene McDermott shoal BRUVS fish modelled abundance (top, total n) and richness (bottom, number of species). The repeated line edge pattern, creating diagonal stripe marks, is attributable to multibeam sampling artifacts at swath transect overlap zones influencing model outputs.

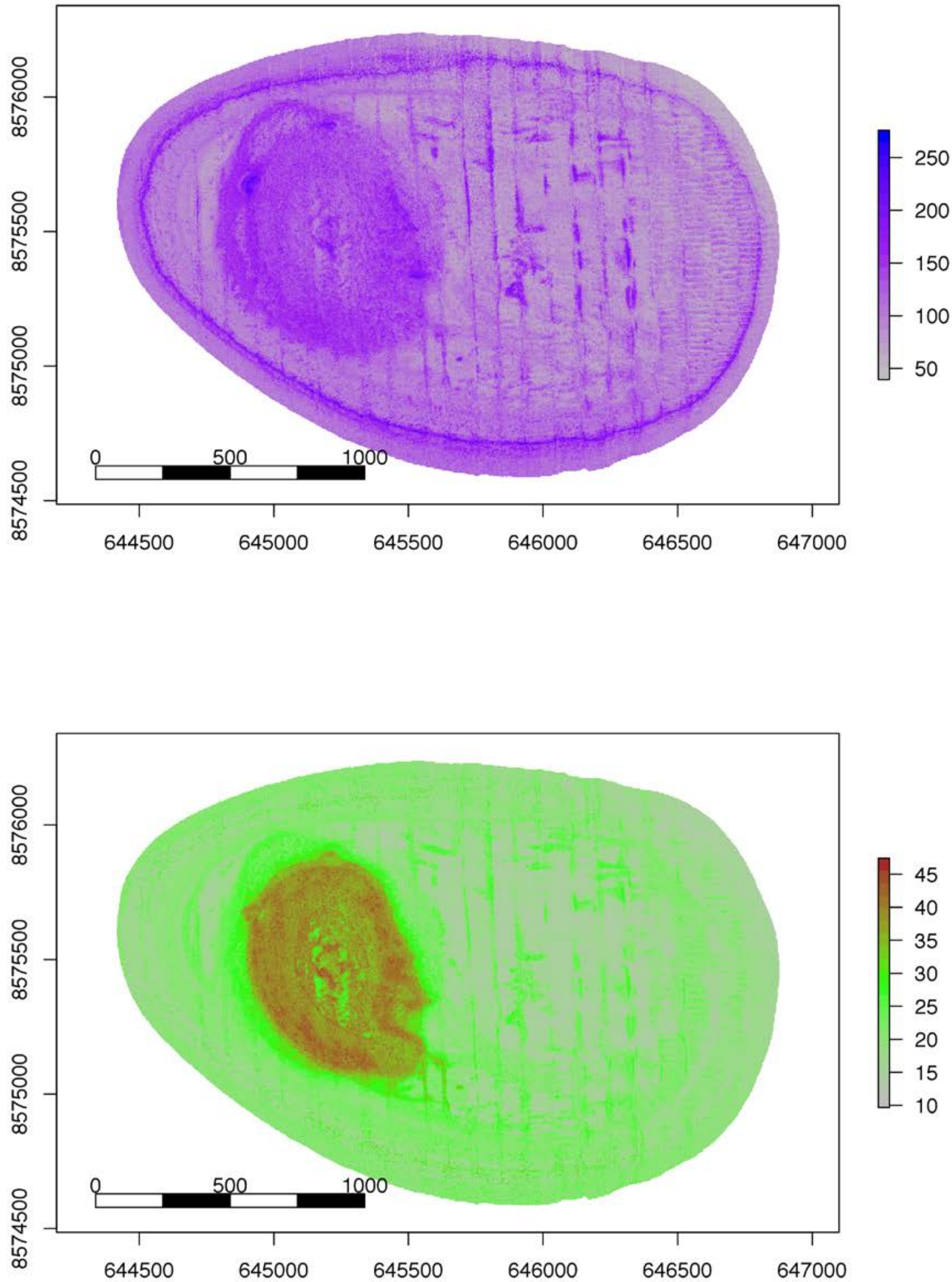
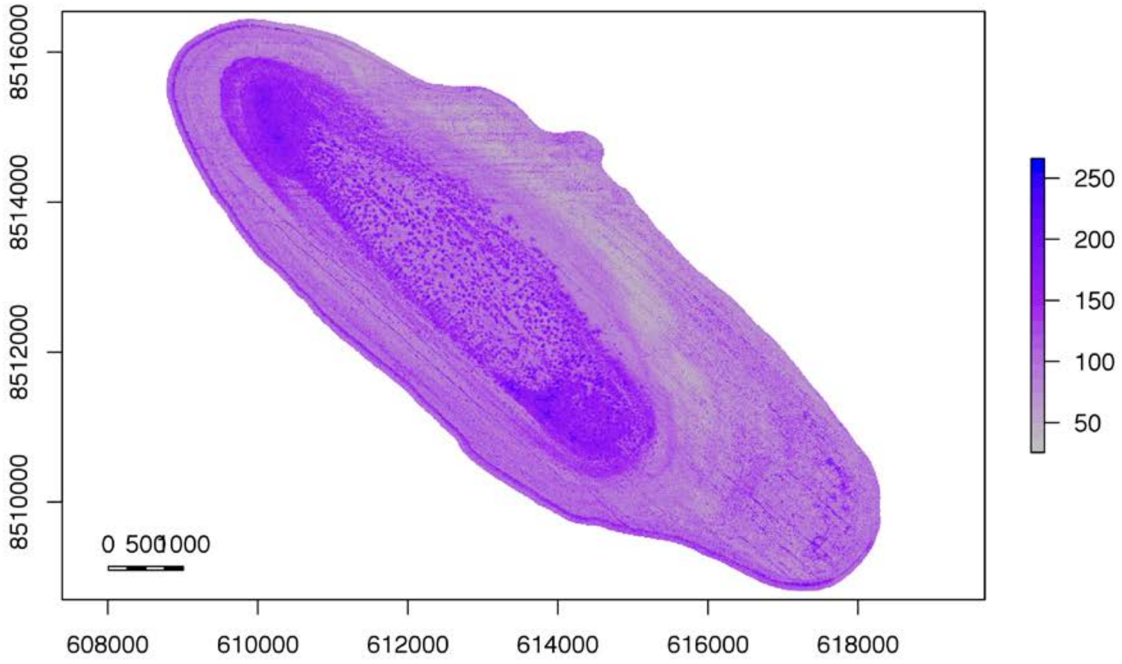


Figure 4.11. Goeree shoal BRUVS fish modelled abundance (top, total n) and richness (bottom, number of species). The repeated line edge pattern, creating vertical strip marks, is attributable to multibeam sampling artifacts at swath transect overlap zones influencing model outputs



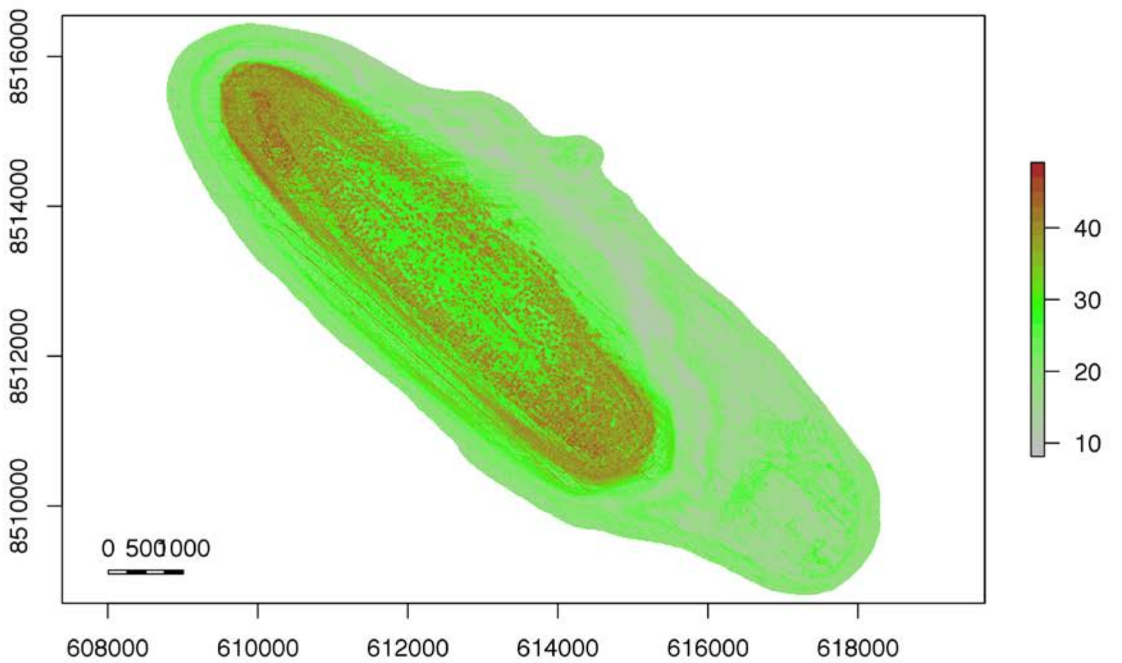
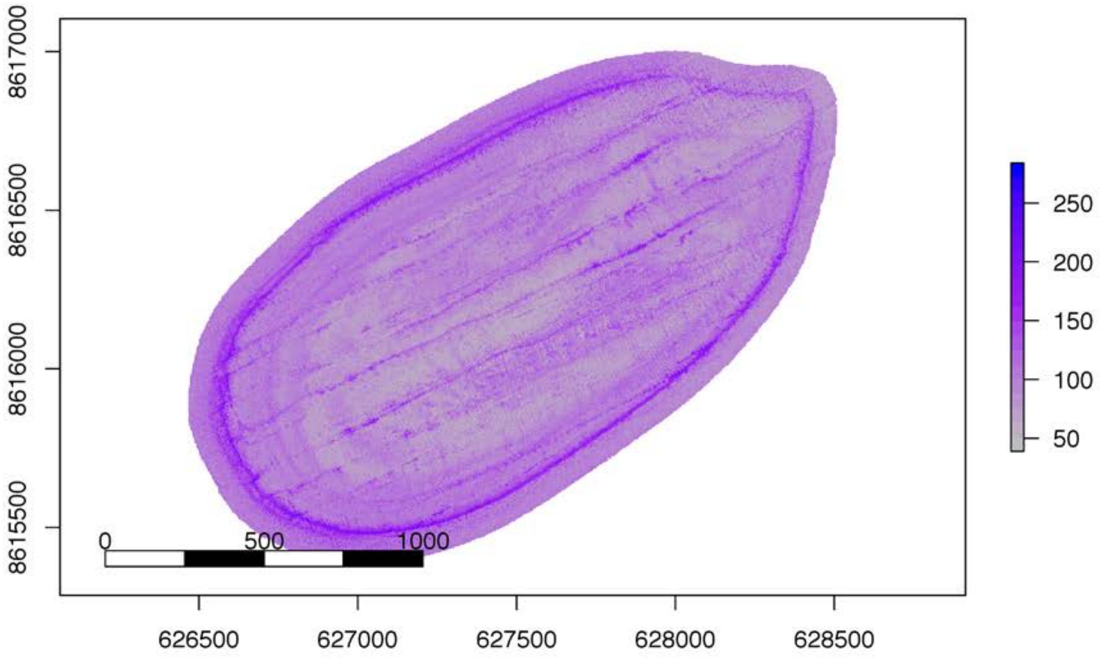


Figure 4.12. Heywood shoal BRUVS fish modelled abundance (top, total n) and richness (bottom, number of species).



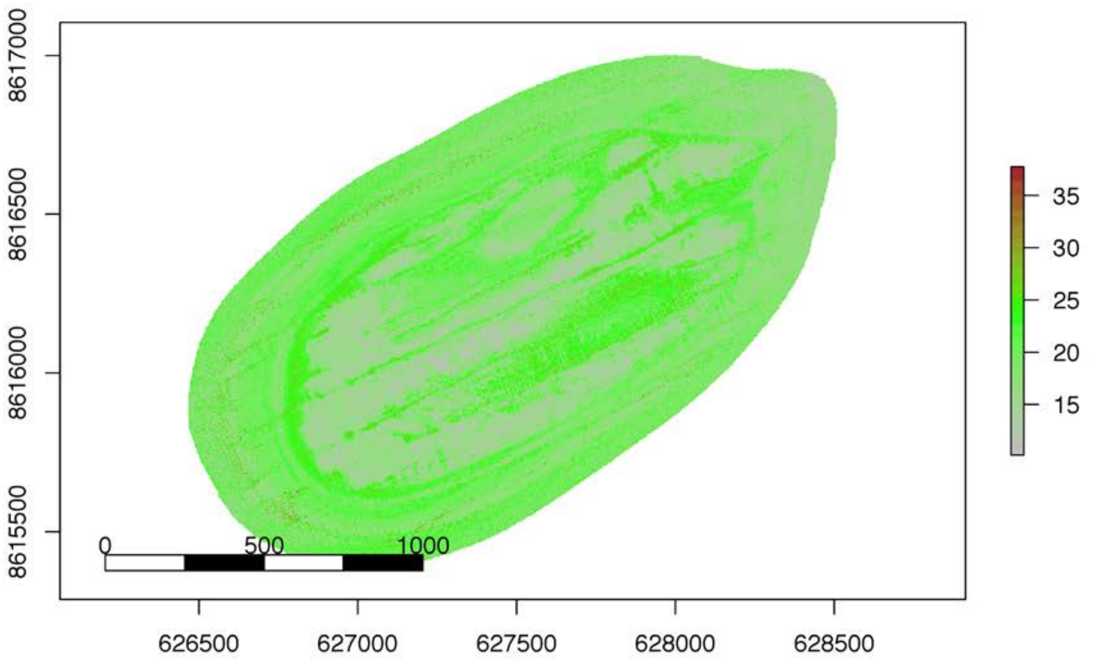
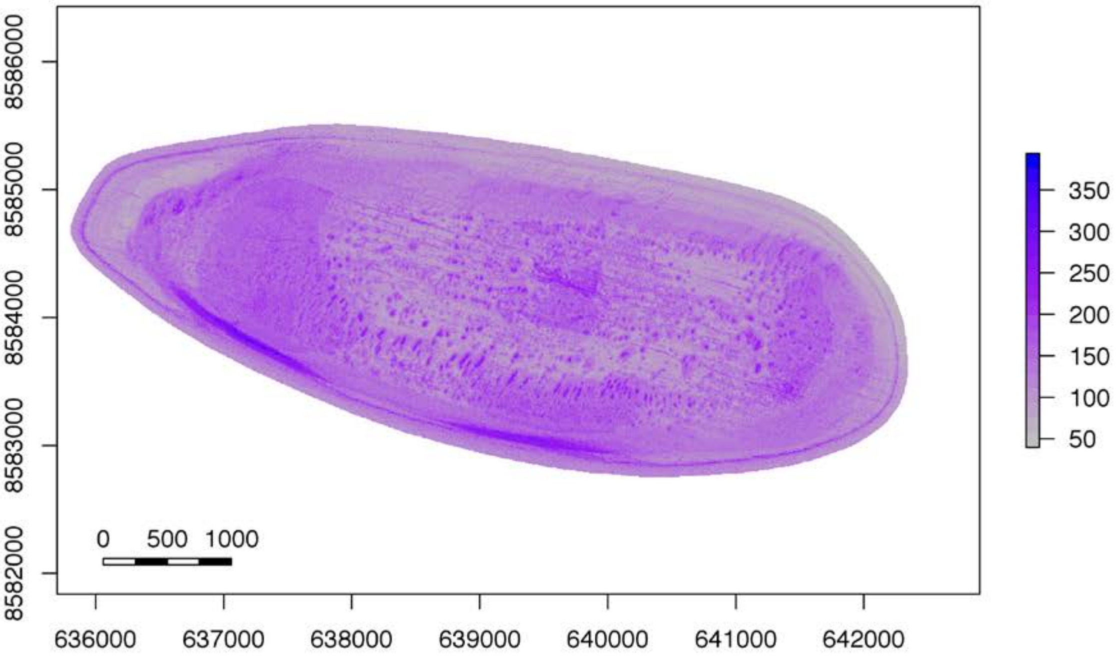


Figure 4.13. Shoal 25 BRUVS fish modelled abundance (top, total n) and richness (bottom, number of species). Some line edge pattern, appearing as diagonal stripe marks, is attributable to multibeam sampling artifacts at swath transect overlap zones influencing model outputs.



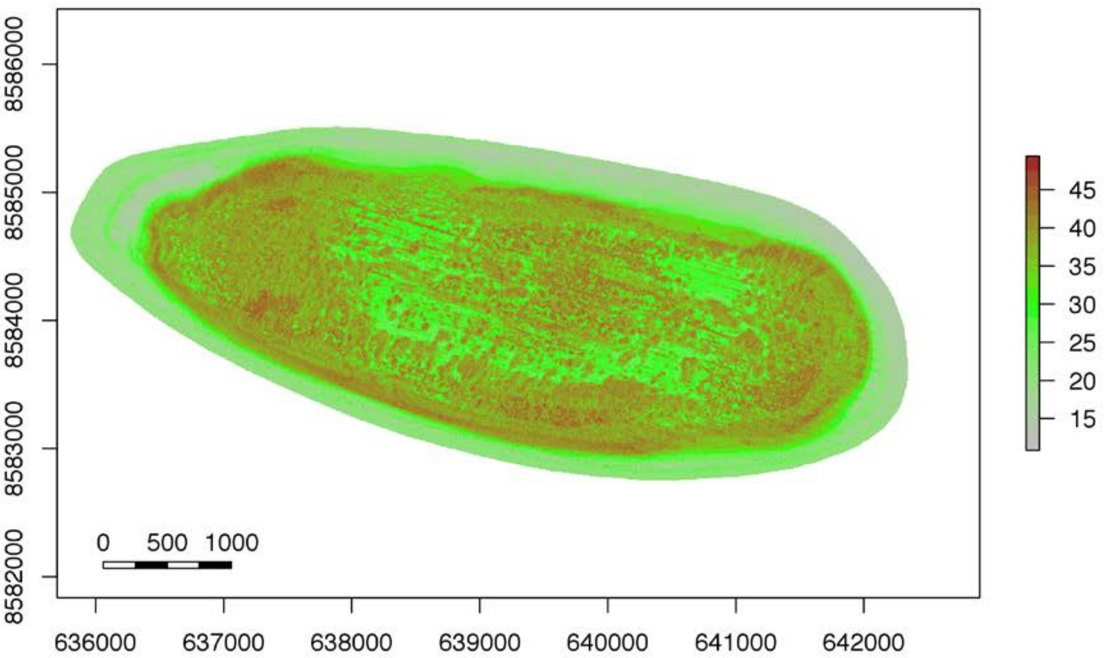


Figure 4.14. Vulcan shoal BRUVS fish modelled abundance (top, total n) and richness (bottom, number of species)

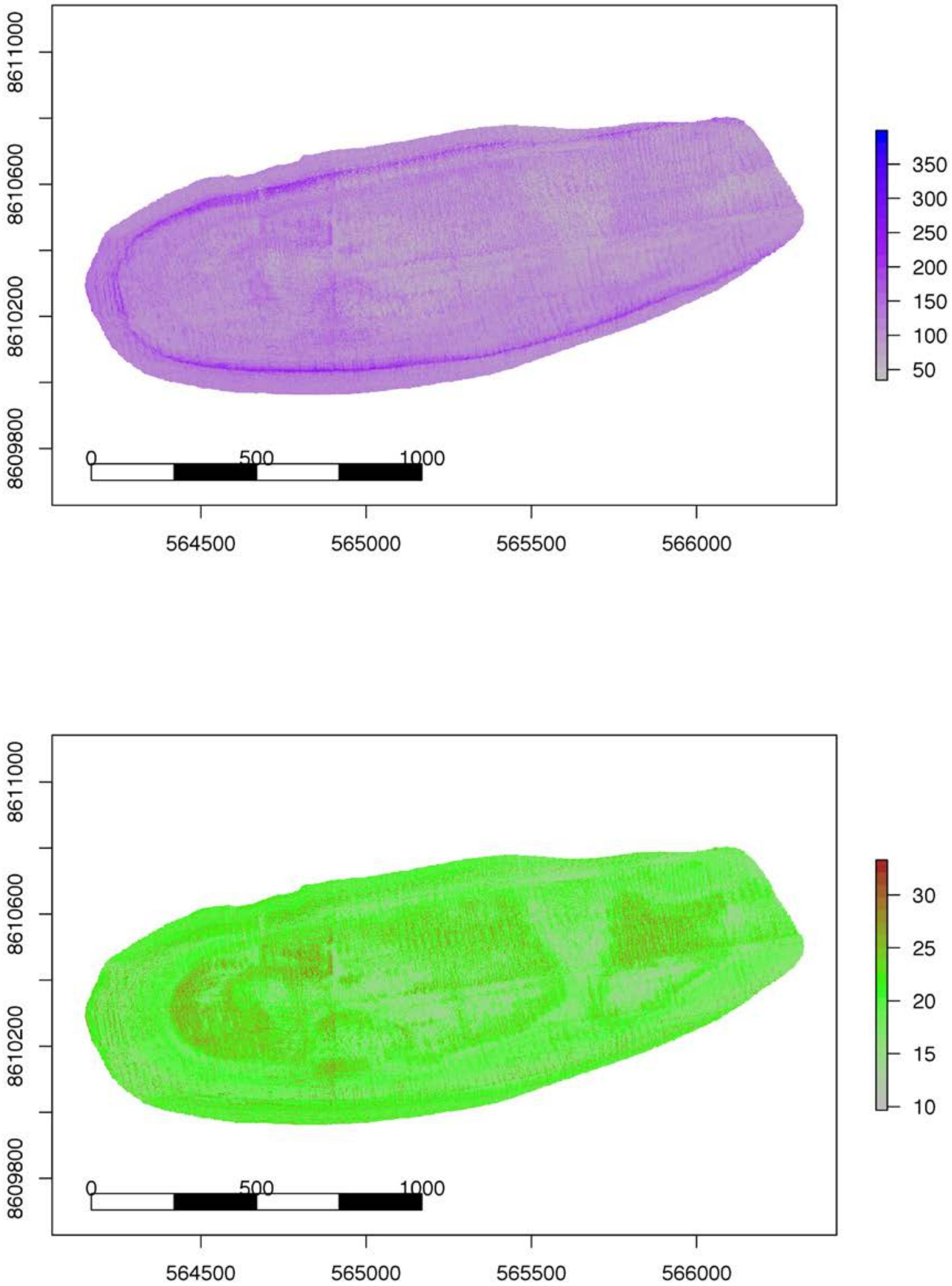


Figure 4.15. Wave Governor Bank BRUVS fish modelled species abundance (top, total n) and richness (bottom, number of species).

4.3.2 Explaining and predicting species richness and abundance using environmental covariates and indices of oil exposure

A map of the shoals, with symbols scaled by richness and abundance, showed no simple pattern in relation to the Montara well head platform location, but there was an obvious east-west, cross-shelf (longitudinal) gradient, as well as a latitudinal spread, in location of the shoals in relation to the Montara well head platform (Figure 4.16).

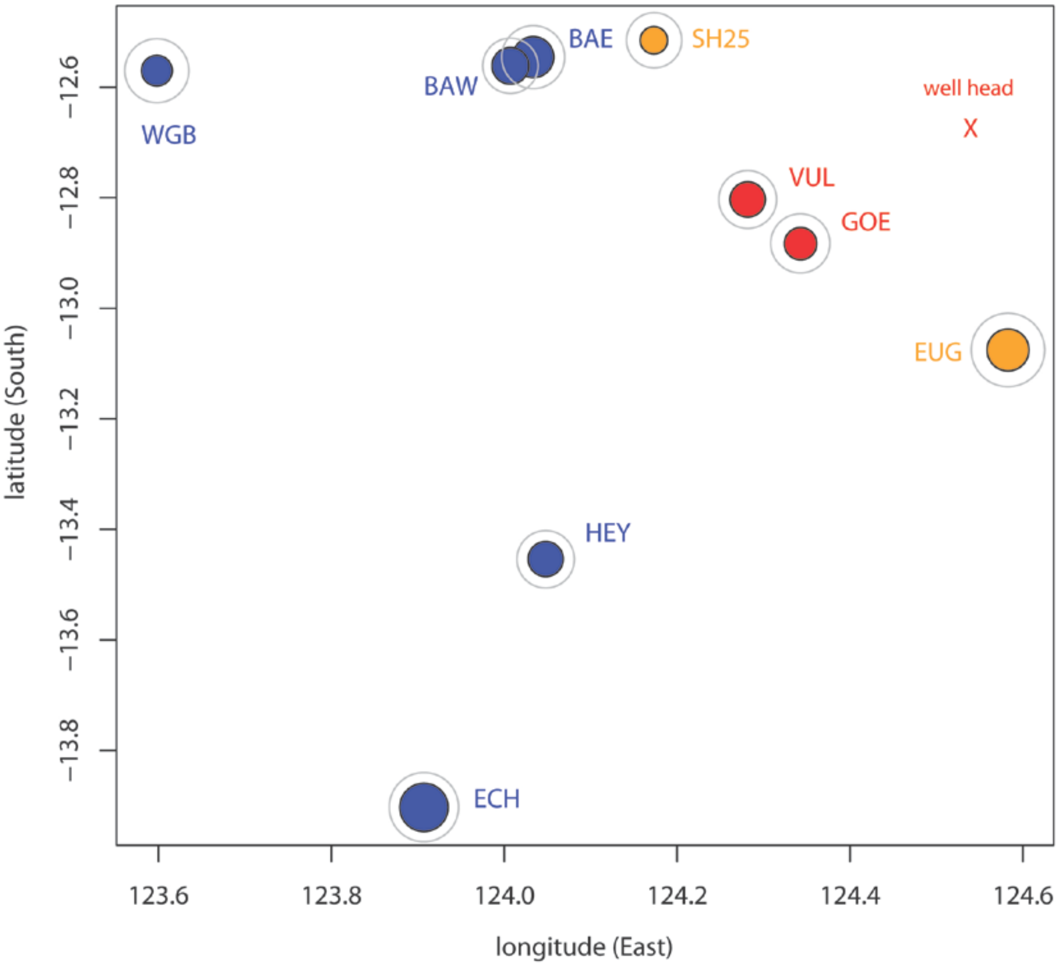


Figure 4.16. Location of the 9 shoals in relation to the MWP, with shoal symbols scaled to average richness. The radii of outer circles surrounding shoal symbols are scaled to average total abundance of fish sampled by BRUVS (*MaxN*). Shoals are coloured by their "exposure category" from low (blue) to medium (orange) to high (red) exposure . There were no obvious differences between sites near and far from the Montara well head platform.

The aggregated boosted regression tree models (ABT) showed clearly that the major influences on species richness were depth and the presence (%cover) of reefal substrata (not necessarily live coral), and much less so the aspect of the BRUVS site (Figure 4.17). The aspect direction (asp.dir) represented the direction toward which the seafloor was sloping where the BRUVS were deployed. The cover of reefal substrata in the field of view, depth and aspect accounted for over 75% of the variation in richness. The greatest influence on species richness of an indicator related to the uncontrolled release was only 1.34% for distance from the uncontrolled release (Table 4.3).

In contrast, the direction of the slope at each BRUVS deployment had a major influence on total abundance of fishes (Figure 4.18), and seafloors with coverage of any type of epibenthos (i.e. low levels of "%bare") (Table 4.4) had higher abundance of fishes on average than stations with no epibenthos. BRUVS set on slopes facing quadrants between north and east (particularly NE and ENE) had much lower than average total abundance of fish.

Partial interaction plots for species richness (Figure 4.19) showed that sites close to the Montara well head platform were spread over a narrow range of longitudes, but there was a slight indication for more species further from the Montara well head platform, given the longitudinal position. This minor influence appeared to comprise a change in less than two species across the entire range of data values (Figure 4.17). However, the response curve for "spilldist" lay within two standard errors about the mean value of richness in the entire dataset (Figure 4.19), so the interpretation of these trends is problematic.

Partial interaction plots for total fish abundance showed that abundance varied most between bare seafloors and those with any reefal substrata, at all depths (Figure 4.18). BRUVS on seafloors dominated by reefal substrata had about 20 more fishes, on average, than bare sea beds at any depth (Figure 4.20). Aspect and the amounts of bare seafloor and reefal substrata in the field of view accounted for over 52% of the influence on abundance. The highest indicator of the uncontrolled release (spilldist) had an influence of only 1.26% (Table 4.4).

These analyses ranked the distance from the Montara well head platform 9th, the duration of oil exposure 21st, and the sediment hydrocarbon concentration 30th in influencing species richness (Table 4.3). In terms of predicting total (pooled) fish abundance, these ranks were even lower (13th, 23rd, 37th) (Table 4.4).

Table 4.3. Influence of 41 explanatory covariates, in decreasing order of importance, on the response of species richness in aggregated boosted regression trees. The cover of reefal substrata in the field of view, depth and aspect accounted for over 75% of the influence on richness. The highest influence of an indicator related to the uncontrolled release was only 1.34% for spilldist. See Table 4.1 for full names of covariates.

Rank	Covariate	%influence
1	calc.rf	33.93
2	depth	25.75
3	asp.dir	11.88
4	bare	5.28
5	mssv.crl	3.85
6	sft.crl	2.47
7	rbbl	1.63
8	lon	1.38
9	spilldist	1.34
10	compass	1.20
11	sndy	1.20
12	std5	1.14
13	grvl	0.89
14	curv	0.82
15	lat	0.82
16	hyp10	0.75
17	hyp5	0.71
18	rng5	0.50
19	rng10	0.46
20	hyp25	0.43
21	oilhours	0.43
22	slp	0.42
23	std10	0.41
24	sol.crl	0.39
25	hyp50	0.33
26	shoalarea	0.30
27	rng50	0.23
28	std50	0.22
37	bldr	0.02
38	whps	0.00
39	mcralg	0.00
40	Hyd	0.00
41	znthd	0.00

Table 4.4. Influence of 41 explanatory covariates, in decreasing order of importance, on the response of transformed fish abundance (4th root *MaxN*) in aggregated boosted regression trees. Aspect, and the amounts of bare seafloor and reefal substrata in the field of view, accounted for over 52% of the influence on abundance. The highest indicator of the uncontrolled release (spilldist) had an influence of only 1.26%.

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Rank	covariate	%influence
1	asp.dir	27.94
2	bare	13.23
3	calc.rf	11.48
4	sndy	9.56
5	depth	5.81
6	grvl	3.46
7	sft.crl	3.42
8	compass	2.44
9	lon	2.39
10	mssv.crl	2.27
11	hyp5	2.04
12	lat	1.61
13	spilldist	1.26
14	hyp25	1.23
15	curv	1.22
16	slp	1.11
17	hyp10	0.91
18	rbbl	0.90
19	std5	0.89
20	sol.crl	0.76
21	std50	0.73
22	hyp50	0.72
23	oilhours	0.70
24	rng50	0.64
25	rng25	0.53
26	std10	0.50
27	shoalarea	0.45
28	std25	0.39
29	rng10	0.33
30	rng5	0.28
41	mcralg	0.00

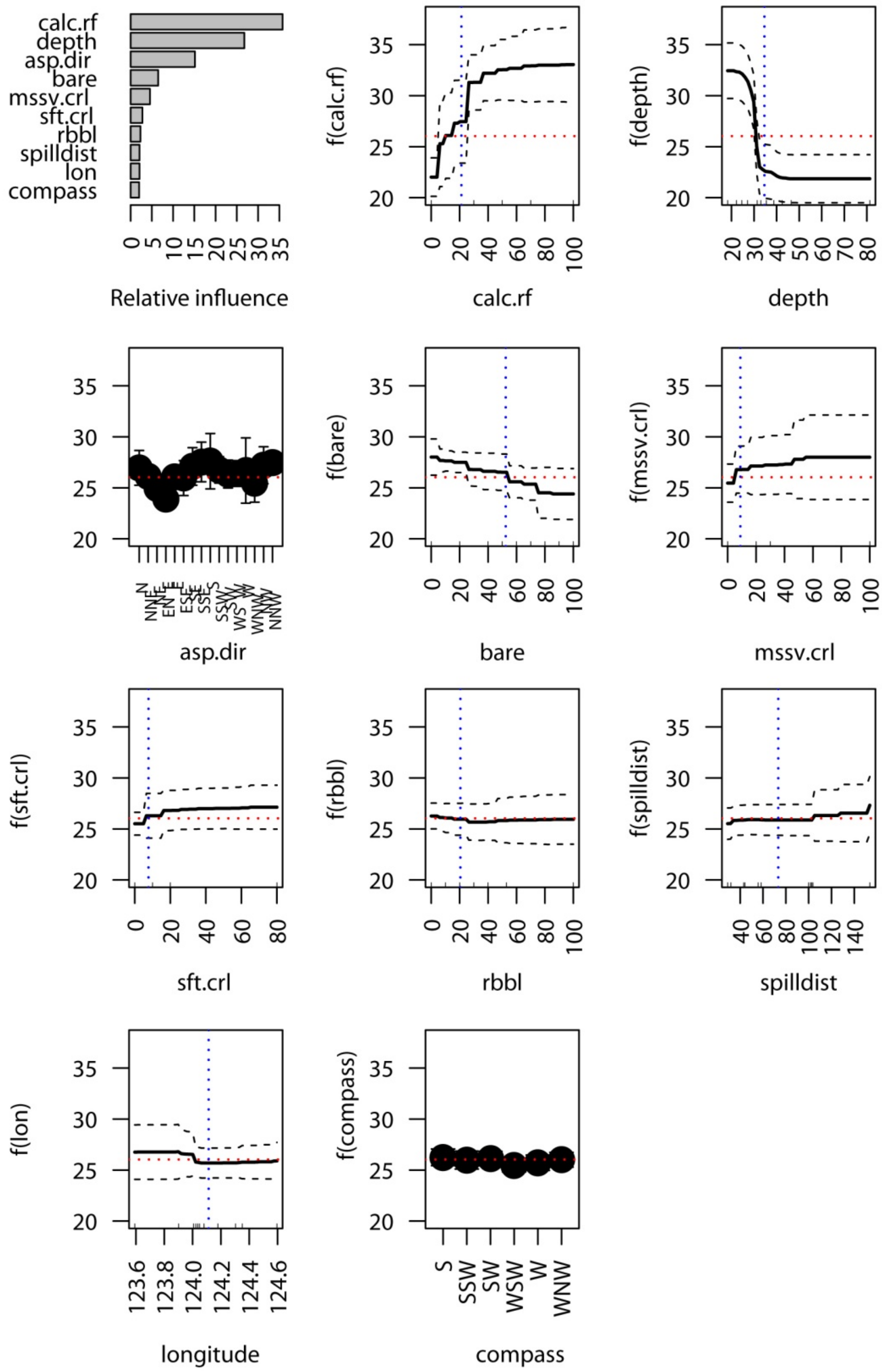

Figure 4.17. Partial dependency plots of the 11 major influences on species richness. The full model of 41 covariates was applied, allowing for 3 way interactions amongst variables. Horizontal dotted lines (red) show the mean abundance across all drops. Vertical dotted lines (blue) show the mean value for each predictor. The response lines show the relationship of abundance as a function of each predictor, with the influence of all other predictors held to a constant (i.e. accounted for). Dotted lines (black) around the response line are 2 standard errors. Drops where seafloor coverage of "calcareous reef" was above the mean of ~20% had higher than average richness, as did depths shallower than 30 m.

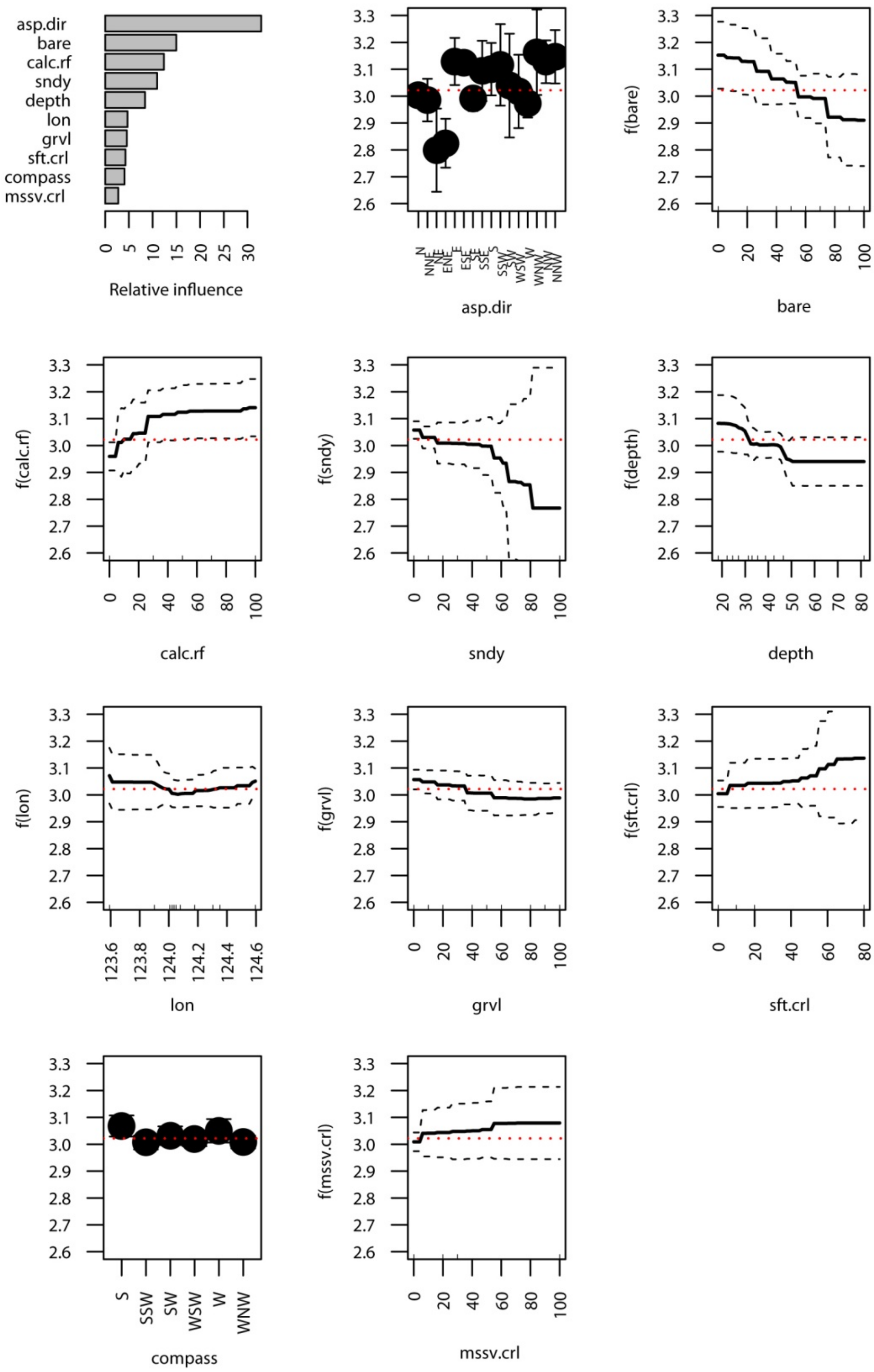

Figure 4.18. Partial dependency plots of the 11 major influences on total abundance (***MaxN*** 4th root transformed). The y-scale is in the transformed units of abundance. The full model of 41 covariates was applied, allowing for 3 way interactions amongst variables. The direction of the slope at each BRUVS deployment ("asp.dir") had major influence, and seafloors with coverage of any type of epibenthos (low levels of "%bare") had higher abundance on average. BRUVS set on slopes facing quadrants between North and East (particularly NE and ENE) had much lower than average fish abundance. All conventions follow Figure 4.17.

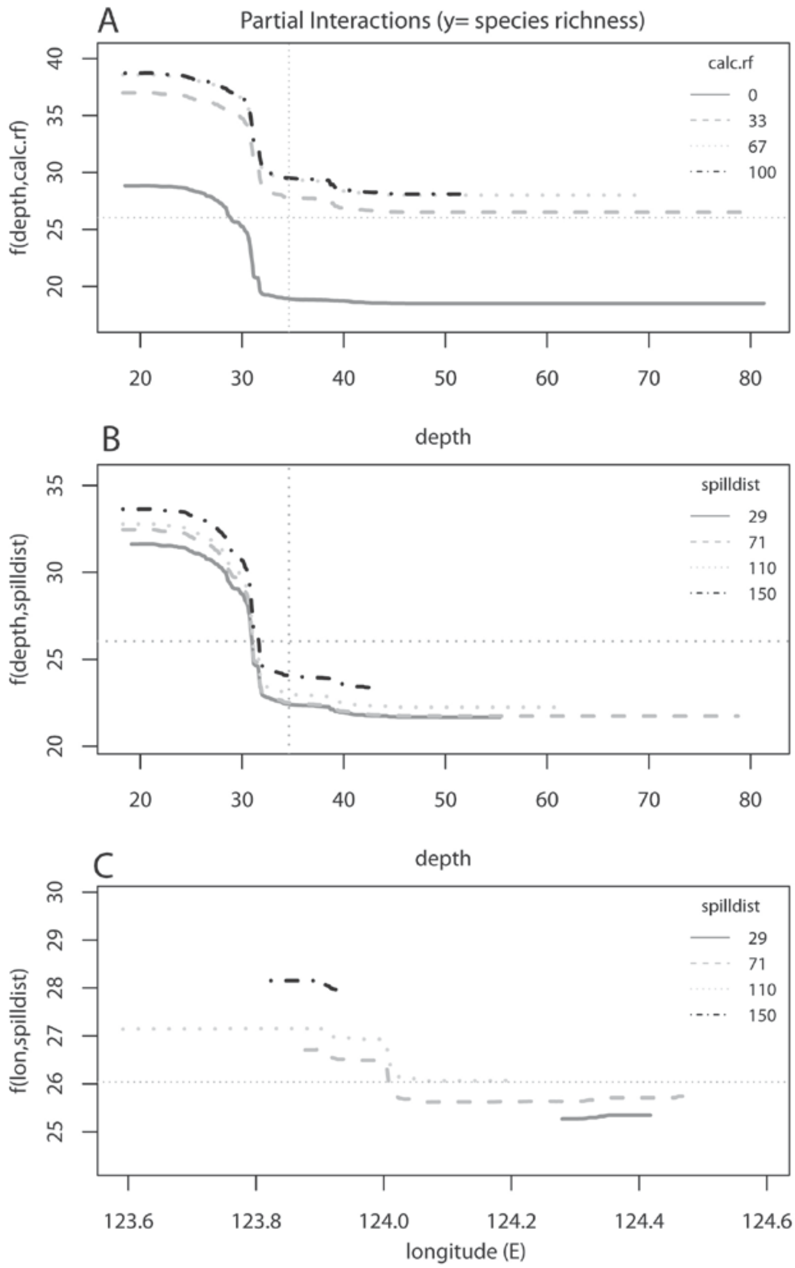

Figure 4.19. Partial interaction plots for the response of species richness (raw scale) as a function of (A) % calcareous reef given depth, (B) spilldist given depth, and (C) spilldist given longitude. BRUVS on seafloors dominated by reefal substrata had about 8-10 more species, on average, than bare seabeds, at all depths. However, there was less than 2 species variation across all distances from the Montara well head platform (MWHP), given depth. Sites close to the MWHP were spread over a narrow range of longitudes, but there was a slight indication for more species further from the MWHP, given the longitudinal position. All other conventions follow Figure 4.17.

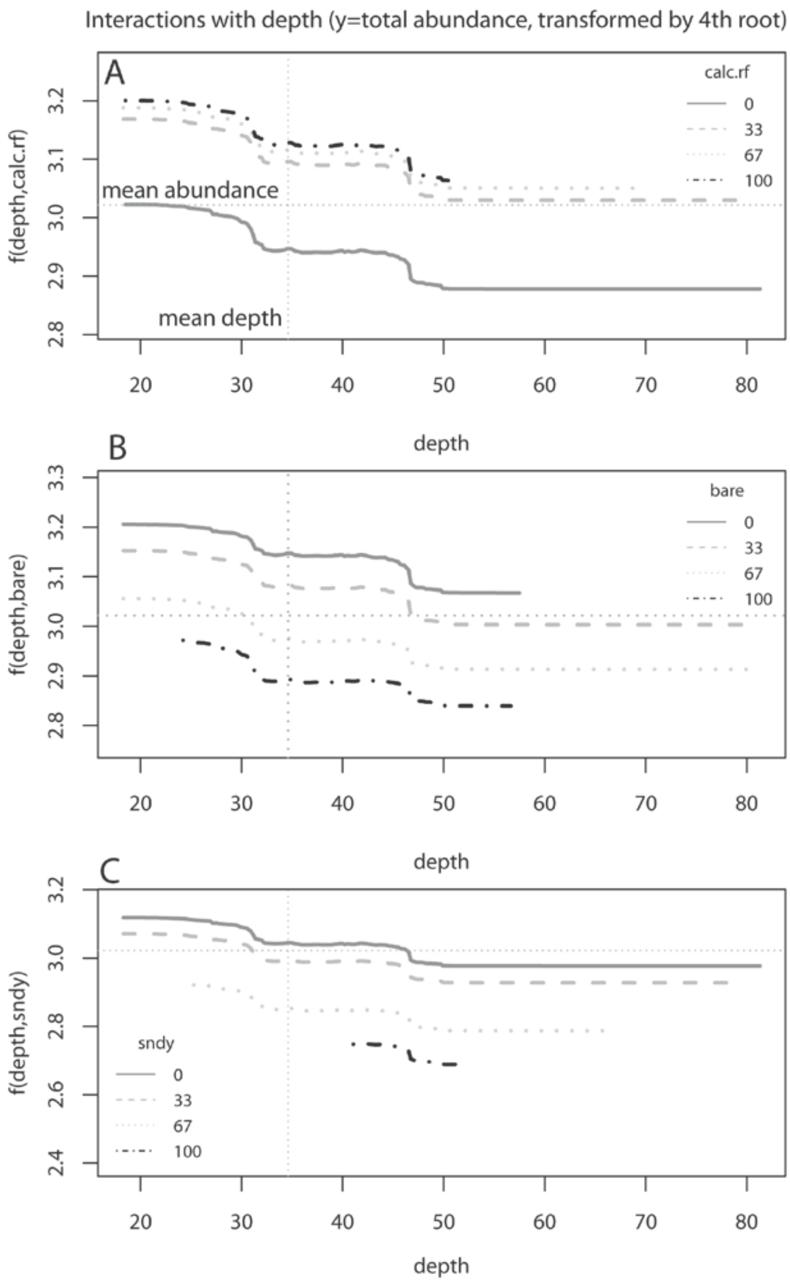

Figure 4.20. Partial interaction plots for the response of total abundance (*MaxN* 4th root transformed) as a function of (A) % calcareous reef given depth, (B) % bare given depth, and (C) % sandy given depth. Abundance varied most between bare seafloors and those with any reefal substrata, at all depths. BRUVS on seafloors dominated by reefal substrata had about 20 more fish individuals, on average, than bare seabeds, at all depths. All other conventions follow Figure 4.17.

4.3.3 Identifying and mapping fish community assemblages using environmental covariates and indices of oil exposure.

The best tree structure from a multivariate analysis of the abundance of the 185 most common species, predicted by the full suite of 41 explanatory covariates, recognised six fish communities amongst the shoals, based on depth, the amount of reefal substrata in the BRUVS field of view, and the size (area) of the shoal from which each sample was taken (Figure 4.21). The Dufrêne-Legendre species indicators (DLI) characterising each branch and each terminal node (leaf) are shown in Table 4.5 and Figure 4.22. In competition with the numerous biotic and abiotic variable influences, indicators of the gradient away from the uncontrolled release were not important as primary splitting variables, or as surrogates. There was also no obvious evidence that smaller fish species were more common as indicator species on the shoals further from the Montara well head platform platform.

The hierarchical nature of the tree allows examination of ubiquitous species with DLI at the "stump" (e.g. the most common *Lethrinus rubrioperculatus*) and those species characterising the terminal communities. For example, the reef-associated serranids *Cephalopholis* and *Variola*, and the butterflyfishes *Chaetodon selene and C. trifascialis* were representative of the community named "*shallow.higher.reef.small.shoals*". This community was moderate in size, in terms of the number of member BRUVS sites, but had much higher richness and abundance (Table 4.6), typical of shallow, reefal habitats in the tropics. Some communities had no DLI species (e.g. node 4; "*deep.low.reef*"), because they comprised a mix of species found elsewhere in higher predominance and abundance.

Schematic maps of the communities (Figure 4.23) showed the major differences amongst each of the nine shoals in the oil spill gradient, in terms of the abundance and spatial distribution of fish communities. The largest shoals (such as Heywood) had the most communities, whilst the smallest shoals sometimes were inhabited by only one (Shoal 25) or two communities (Wave Governor Bank). Shoal tops had more diversity in the membership of BRUVS sites amongst community types compared to the shoal rims.

Species accumulation curves derived for the six fish assemblages showed that the curves were still ascending toward an asymptote in the assemblages (Figure 4.6). The curves were steeper for the assemblages characterising sites with higher reefal composition of the substrata, reflecting the four-fold difference in mean species richness between *deep.low.reef.large.shoals* (n=26 sites) and *shallow.higher.reef.small.shoals* of the same size (Table 4.6).

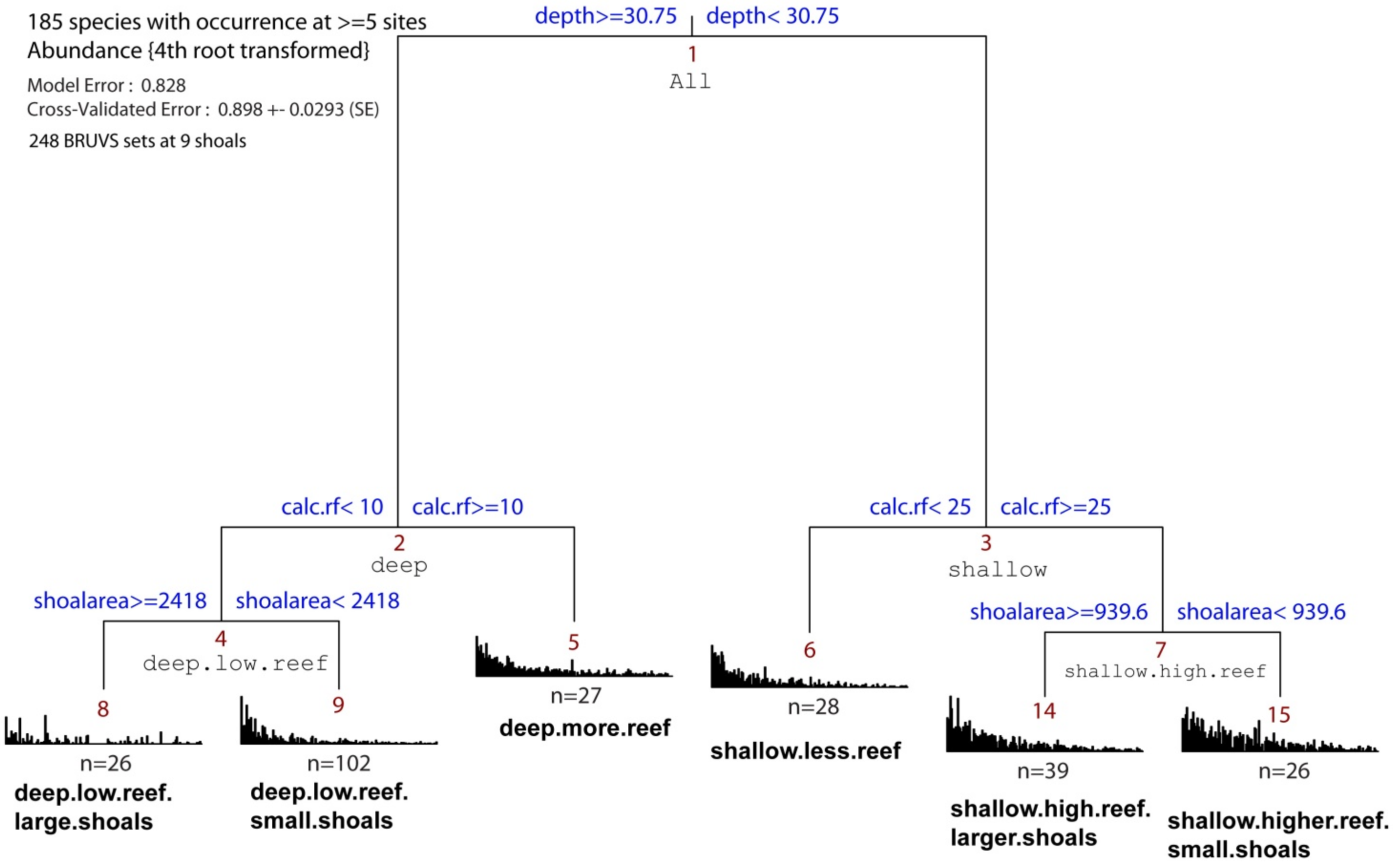

Figure 4.21. The best tree structure from a multivariate analysis of the abundance of species predicted by the full suite of 41 explanatory covariates. The subset of 185 fish species selected for this analysis was present on at least 5 BRUVS, and their abundances were transformed by 4^{th} root. The model had high error predicting the abundance of all these species simultaneously, but the best fit (lowest prediction error) recognised 6 fish assemblages amongst the shoals, based on depth, the amount of reefal substrata in the BRUVS field of view, and the area of the shoal where each sample was taken. Histograms on the “leaves” show the abundance of each species and the number of sites (*n*) are given with node names and node numbers.

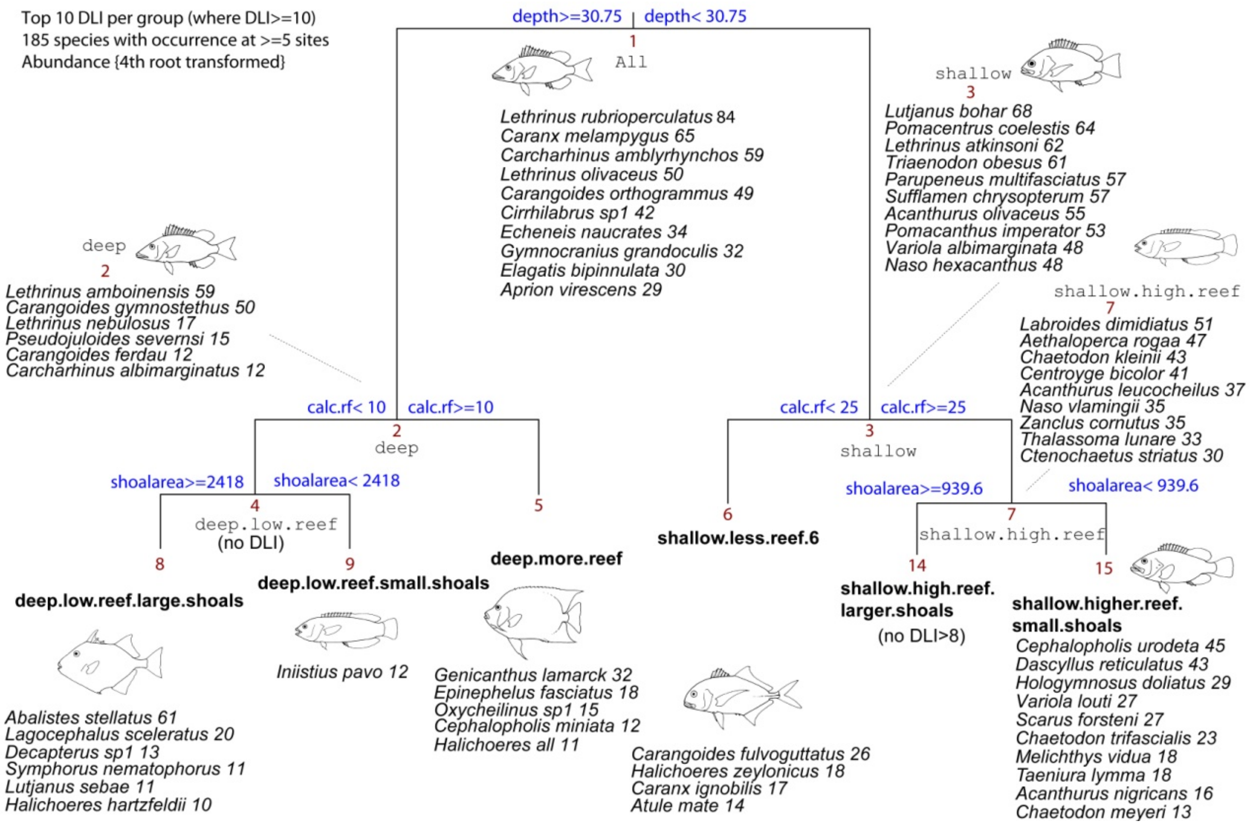

Figure 4.22. The multivariate prediction and regression tree from Figure 4.21 showing the Dufrêne-Legendre species indicators (DLI) characterising each branch and each terminal node (leaf). The DLI value is an index of fidelity and specificity of a species to a tree node. The hierarchical nature of the tree allows examination of which species are ubiquitous (e.g. *Lethrinus rubrioperculatus*) with DLI at the "stump", and which species characterise the terminal assemblages. For example, *Cephalopholis urodeta* is a major representative of the assemblage named "*shallow.higher.reef.small.shoals*". Some assemblages have no DLI species (e.g. node 4; "*deep.low.reef*"), because they comprise a mix of species found elsewhere in higher predominance and abundance. Only the top 10 DLI (above DLI=9) are shown for each node. The full list is given in Table 4.5.

Table 4.5. The Dufrêne -Legendre indices (DLI) for each of the 185 species analysed as the multivariate response in Figure 4.21. The DLI species, and their values, are shown for each node of the tree. These nodes include the hierarchical branches, and the terminal nodes comprising the 6 fish assemblages (in bold).

Nodename	Tree node	
All	1	*Lethrinus rubrioperculatus (84), Caranx melampygus (65), Carcharhinus amblyrhynchos (59), Lethrinus olivaceus (50), Carangoides orthogrammus (49), Cirrhilabrus sp1 (42), Echeneis naucrates (34), Gymnocranius grandoculis (32), Elagatis bipinnulata (30), Aprion virescens (29), Sufflamen fraenatum (27), Siganus argenteus (24), Parupeneus cyclostomus (22), Gymnosarda unicolor (18), Dasyatis kuhlii (18)*
Deep	2	*Lethrinus amboinensis (59), Carangoides gymnostethus (50), Lethrinus nebulosus (17), Pseudojuloides seversni (15), Carangoides ferdau (12), Carcharhinus albimarginatus (12), Carangoides coeruleopinnatus (10), Lethrinus sp1 (9), Gymnothorax all (4)*
Shallow	3	*Lutjanus bohar (68), Pomacentrus coelestis (64), Lethrinus atkinsoni (62), Triaenodon obesus (61), Parupeneus multifasciatus (57), Sufflamen chrysopterum (57), Acanthurus olivaceus (55), Pomacanthus imperator (53), Variola albimarginata (48), Naso hexacanthus (48), Apolemichthys trimaculatus (47), Balistoides viridescens (41), Acanthurus grammoptilus (40), Naso lituratus (40), Parapercis sp1 (40)*
Deep, low reef	4	No DLI species
Deep, More reef	**5**	*Genicanthus lamarck (32), Epinephelus fasciatus (18), Oxycheilinus sp1 (15), Cephalopholis miniata (12), Halichoeres all (11), Canthidermis maculatus (9), Parupeneus barberinoides (8), Pygoplites diacanthus (7), unk all (7), Caranx sexfasciatus (6), Scarus rivulatus (5), Lethrinus semicinctus (5), Chaetodon lunulatus (4), Epinephelus malabaricus (4)*
Shallow, Less reef	**6**	*Carangoides fulvoguttatus (26), Halichoeres zeylonicus (18), Caranx ignobilis (17), Atule mate (14), Novaculichthys taeniourus (7), Acanthurus dussumieri (6), Naso annulatus (5), Naso unicornis (4)*
Shallow, High reef	7	*Labroides dimidiatus (51), Aethaloperca rogaa (47), Chaetodon kleinii (43), Centropyge bicolor (41), Acanthurus leucocheilus (37), Naso vlamingii (35), Zanclus cornutus (35), Thalassoma lunare (33), Ctenochaetus striatus (30), Chromis margaritifer (30), Chromis weberi (29), Halichoeres hortulanus (21), Chlorurus sordidus (21), Macolor niger (21), Centropyge tibicen (19), Centropyge vroliki (18)*
Deep, low reef, Large shoals	**8**	*Abalistes stellatus (61), Lagocephalus sceleratus (20), Decapterus sp1 (13), Symphorus nematophorus (11), Lutjanus sebae (11), Halichoeres hartzfeldii (10), Sphyraena barracuda (8), Heteromycteris hartzfeldi (4)*
Deep, low reef, Small shoals	**9**	*Iniistius pavo (12), Hemitriakis falcata (5), Ptereleotris sp1 (3)*
Shallow, high reef, Large shoals	**14**	*Chaetodon selene (8), Pomacanthus sexstriatus (8), Lutjanus lemniscatus (4)*
Shallow, Higher reef, small shoals	**15**	*Cephalopholis urodeta (45), Dascyllus reticulatus (43), Hologymnosus doliatus (29), Variola louti (27), Scarus forsteni (27), Chaetodon trifascialis (23), Melichthys vidua (18), Taeniura lymma (18), Acanthurus nigricans (16), Chaetodon meyeri (13), Chaetodon ornatissimus (13), Pseudodax moluccanus (11), Siganus punctatus (11), Choerodon jordani (10), Chaetodon baronessa (10)*

Figure 4.23. Schematic maps of the 9 shoals showing which of the 248 BRUVS sites are members of each of the six fish assemblages identified by the regression tree in Figure 4.21. Each symbol is scaled by species richness to the maximum recorded in the dataset, and coloured by membership of the six assemblages. The major point to note is how different each of the nine shoals was in the number and spatial distribution of fish assemblages. The largest shoals had the most assemblages, whilst the smallest shoals sometimes were inhabited by only one (Shoal 25) or two assemblages (Wave Governor Bank). Shoal tops had more diversity in the membership of BRUVS sites amongst assemblage types compared to the shoal rims.

Table 4.6. Summaries of the abundance and species richness for the 6 fish assemblages identified in the multivariate tree (Figure 4.21). The grand count of all fish sighted in an assemblage is shown as ∑∑***MaxN***, with the total number of species (richness, *S*). The range in richness and abundance for each of the *n* BRUVS sites within an assemblage is shown by the range and mean in *S* and ∑***MaxN.*** The node number and assemblage name, from Figures 4.21 and 4.22, is accompanied by the total number of DLI species (*n*DLI) from Table 4.5.

						Richness (*S*)		**∑*MaxN***	
node	***n***	**Assemblage name**	***S***	**∑∑*MaxN***	***n*DLI**	range	mean	range	mean
8	26	deep.low.reef. large.shoals	85	1176	8	(1 - 25)	(9.8 ± 6.3)	(2 - 215)	(45.2 ± 47.5)
9	102	deep.low.reef. small.shoals	207	8746	3	(4 - 40)	(17.4 ± 7.9)	(9 - 578)	(85.7 ± 81.4)
5	27	deep.more.reef	221	3871	14	(14 - 72)	(31.7 ± 14.3)	(32 - 494)	(143.4 ± 108.6)
6	28	shallow.less.reef	161	2659	8	(11 - 48)	(28.6 ± 10.8)	(32 - 222)	(95 ± 53.7)
14	39	shallow.high.reef. larger.shoals	225	5114	3	(17 - 67)	(40.4 ± 11.7)	(36 - 258)	(131.1 ± 57.8)
15	26	shallow.higher.reef. small.shoals	197	4125	19	(31 - 65)	(46 ± 8.9)	(54 - 322)	(158.7 ± 72.3)

4.3.4 Predicting species occurrence (presence/absence) using environmental covariates and indices of oil exposure

Univariate ABT models were constructed for the 54 species occurring on at least 15 % (n=40 of the 248 samples) to predict the probability of their occurrence (presence/absence) (Table 4.7; Appendix 4.4 - Table A4.4.1). Relative prediction errors for these models were not always related to how common a species was in the data set, but there was relatively high accuracy for a number of key species (Table 4.7).

In Table A4.4.1, species are ranked in terms of their "predictability" and the explanatory covariates are ranked from left to right in decreasing order of their average influence across all 54 species. In terms of average influence, the direction of the slope at BRUVS sites (asp.dir), depth, and the %cover of reefal substrata were the primary predictors, with a steep drop to the influence of latitude, longitude and distance to the Montara well head platform (spilldist). On average, spilldist had an influence of only 2.8% on predicting the occurrence of the individual species, whereas the influences were much higher for aspect (25.2%), depth (14.4%), % reefal substrata (6.7%), latitudinal position (6.7%) and longitudinal position (5.4%). On average, across the 54 most prevalent species sighted on the BRUVS, the rank of influence in predicting presence/absence of the indices of oil exposure was 6th for distance from the Montara well head platform, 19th for time of exposure to the uncontrolled release, and only 38th for the sediment hydrocarbon concentration. The greatest individual influence was only 5.7% for predicting the presence or absence of the emperor *Lethrinus atkinsoni*. The best model predicted that the probability of occurrence of this emperor was actually 10% higher than average closest to the Montara well head platform.

Table 4.7. The 54 species occurring on at least 15 % (n=40 occurrences) of 248 BRUVS sites, ranked in increasing order of relative prediction error (*rel.pred.err*) in aggregated boosted regression tree (**ABT**) models predicting the probability of their occurrence (presence/absence). Low *rel.pred.err* indicates high accuracy in predicting species occurrence at a BRUVS site. The number *n* (and rank) of occurrences is also shown.

Species	**Family**	***rel.pred.err***	**Rank in dataset**	**occurrences (*n* BRUVS)**
Abalistes stellatus	Balistidae	0.13	38	49
Lethrinus nebulosus	Lethrinidae	0.13	49	42
Sufflamen chrysopterum	Balistidae	0.15	26	67
Chaetodon kleinii	Chaetodontidae	0.15	41	46
Aluterus scriptus	Monacanthidae	0.15	54	38
Lutjanus bohar	Lutjanidae	0.16	5	143
Aethaloperca rogaa	Serranidae	0.16	39	48
Macolor macularis	Lutjanidae	0.16	52	41
Alepes vari	Carangidae	0.17	51	41
Lethrinus rubrioperculatus	Lethrinidae	0.17	1	208
Scarus oviceps	Scaridae	0.17	53	41
Naso lituratus	Acanthuridae	0.17	45	45
Centropyge bicolor	Pomacanthidae	0.18	46	45
Dasyatis kuhlii	Dasyatidae	0.18	48	44
Balistoides conspicillum	Balistidae	0.18	50	41
Lethrinus amboinensis	Lethrinidae	0.18	6	136
(sea snakes) all unknown spp	Hydrophiidae	0.18	42	45
Gymnosarda unicolor	Scombridae	0.18	47	45
Acanthurus leucocheilus	Acanthuridae	0.19	43	45
Carangoides fulvoguttatus	Carangidae	0.19	40	46
Lutjanus rivulatus	Lutjanidae	0.19	37	52
Parupeneus multifasciatus	Mullidae	0.2	20	81
Naso brachycentron	Acanthuridae	0.2	44	45
Acanthurus olivaceus	Acanthuridae	0.2	22	75
Naso vlamingii	Acanthuridae	0.2	32	56
Parapercis sp1	Pinguipedidae	0.21	34	55
Triaenodon obesus	Carcharhinidae	0.21	9	104
Caranx melampygus	Carangidae	0.21	2	160
Carangoides gymnostethus	Carangidae	0.21	14	96
Odonus niger	Balistidae	0.21	35	53
Labroides dimidiatus	Labridae	0.22	19	84
Naso brevirostris	Acanthuridae	0.22	36	52
Parupeneus cyclostomus	Mullidae	0.22	33	55
Scolopsis xenochrous	Nemipteridae	0.24	30	60
Siganus argenteus	Siganidae	0.24	31	60
Pomacanthus imperator	Pomacanthidae	0.25	15	96
Apolemichthys trimaculatus	Pomacanthidae	0.25	16	90
Aipysurus laevis	Hydrophiidae	0.25	29	61
Zanclus cornutus	Zanclidae	0.25	28	65
Carangoides orthogrammus	Carangidae	0.25	8	122
Pomacentrus coelestis	Pomacentridae	0.25	11	102
Balistoides viridescens	Balistidae	0.25	27	65
Naso hexacanthus	Acanthuridae	0.26	12	99
Acanthurus grammoptilus	Acanthuridae	0.26	18	84
Lethrinus atkinsoni	Lethrinidae	0.27	4	146
Sufflamen fraenatum	Balistidae	0.27	25	68
Variola albimarginata	Serranidae	0.28	13	98
Aprion virescens	Lutjanidae	0.29	24	71
Carcharhinus amblyrhynchos	Carcharhinidae	0.3	3	147
Elagatis bipinnulata	Carangidae	0.3	23	74
Gymnocranius grandoculis	Lethrinidae	0.33	21	80
Echeneis naucrates	Echeneidae	0.34	17	85
Lethrinus olivaceus	Lethrinidae	0.37	7	125
Cirrhilabrus sp1	Labridae	0.43	10	104

It is notable that BRUVS at sites sloping toward the north and east had lower than average probability of encountering the large and small planktivores (*Naso hexacanthus* and *Pomacentrus coelestis*) and the converse was true for southward and westward sloping sites (Appendix 4.3; Figures A4.3.3 and A4.3.4). It is possible these southern slopes are the locations where food-rich currents from waves, tides and episodic upwellings impinge. The response curve in Figure A4.3.3 suggested there was a positive influence of *spilldist* of about 10% across the range of distances from the Montara well head platform for *Naso hexacanthus*, but this lay parallel with influence of about 30% increase in probability across the (cross-shelf) decrease in longitude (Figure A4.3.3).

Shallow depths were major influences on probability of encountering the small, schooling planktivore *Pomacentrus coelestis*, with about a 10% decline in habitats where the cover of reefal substrata was less than 20% (Figure A4.3.4). These patterns closely matched those of the piscivorous red bass (*Lutjanus bohar*), which is probably a major predator of these small damselfishes (Figure A4.3.5).

Other predators showed a variety of patterns. Shallow depths below 30 m and aspect direction were major influences on probability of encountering the white-tip reef shark (*Triaenodon obesus*), with an important influence of rubbley seabeds (Figure A4.3.6). The probability of occurrence of the mobile blue-spotted trevally *Caranx melampygus* showed the same pattern, albeit with a higher probability of occurrence on seafloors with very low coverage of sand (Figure A 4.3.7).

For many species, a lower than average probability of occurrence was predicted for BRUVS sites sloping toward the quadrants between north and east. However, the converse was true for the most common species in the data set, the red-spotted emperor *Lethrinus rubrioperculatus*. There were also higher than average probabilities of occurrence at flatter sites for this species where coverage of sand on the seafloor was less than 50% and slopes were less than 10 degrees (Figure A4.3.8). *Lethrinus rubrioperculatus* is a demersal carnivore consuming a large proportion of benthic invertebrates in its diet.

4.3.5 General additive mixed models and linear regression approach

Variability in species richness between shoals, and as a function of habitat and exposure

Species richness per deployment varied among shoals from 15.9 (1.5± SE) at Shoal 25 to 37.5 (2.9± SE) species at Echuca (Appendix 4.5, Table 4.5.4). One way unrestricted permutational ANOVA indicated that overall species richness varied among shoals ($p<0.001$) but that inter-shoal variability was primarily driven by Echuca which differed significantly from Barracuda East ($p=0.001$), Goeree ($p=0.002$), Shoal 25 ($p=0.0000074$), Vulcan ($p=0.014$) and Wave Governor Bank ($p=0.001$); Shoal 25 also differed significantly from Eugene McDermott ($p=0.008$) and Barracuda East ($p=0.001$) as did the latter from Wave Governor Bank ($p=0.046$). All other pairwise comparisons of shoals were non-significant. (Appendix 4.5; Table 4.5.1).

GAMMS indicated that between 38% and 56% of the variation in species richness could be explained by habitat variables (based on $adjR^2$) with calcareous reef and depth the best predictors of species richness ($adjR^2 = 0.56$; Appendix 4.5; Table A4.5.5; Figure 4.24). The addition of an exposure metric was marginally significant with species richness declining as hours of exposure increased ($adjR^2 = 0.58$; Appendix 4.5; Table A4.5.5; Figure 4.24) with longitude also significant ($p=0.01$). Other habitat + exposure models showed similar patterns with minimum hours of exposure marginally significant in relation to gravel and depth, sand

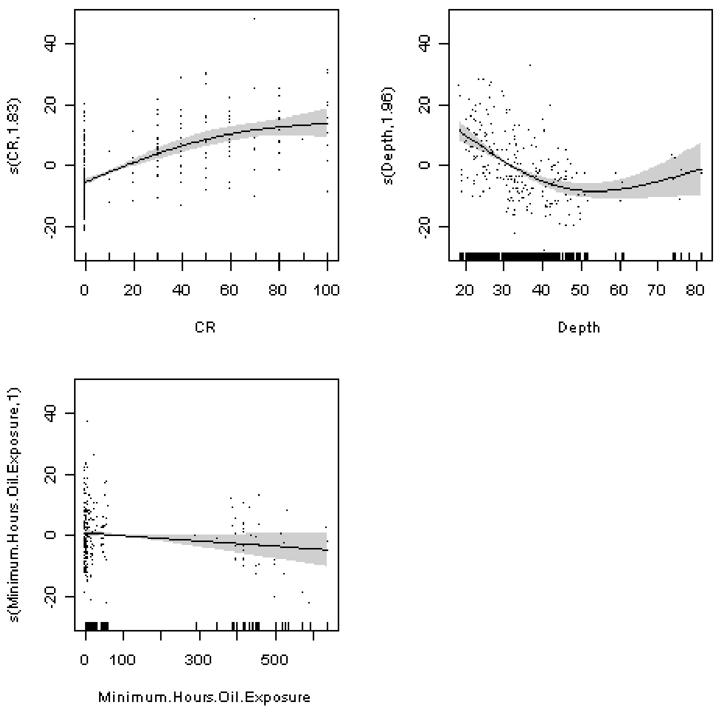

Figure 4.24. GAMMS of species richness (SR) vs (a) calcareous reef (CR) and depth and (b) CR, depth and minimum hours of exposure.

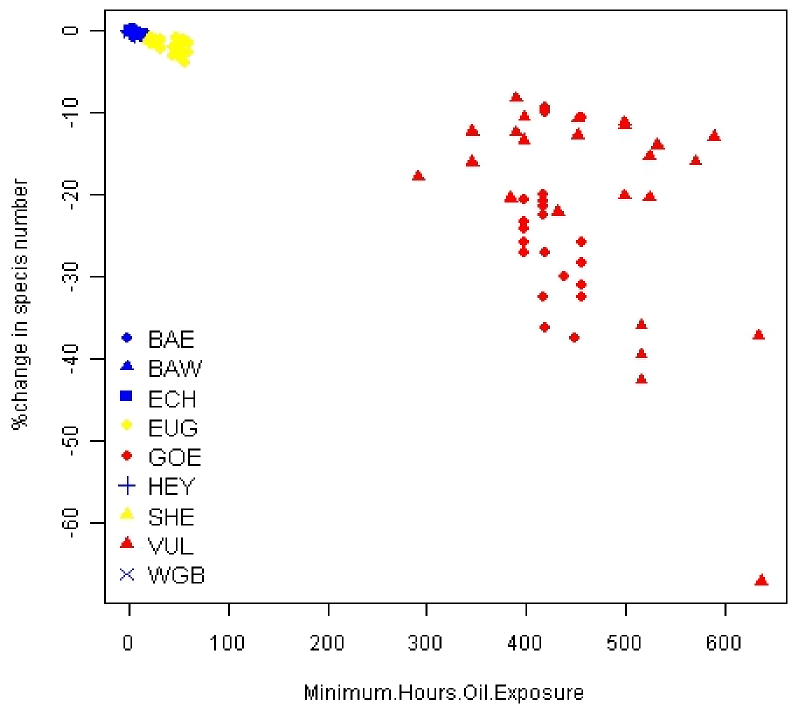

Figure 4.25. Effect size as % of change in species richness vs minimum hours of exposure. % change in SR calculated as ($SR_{hab+exp}$-$SR_{hab+exp=none}$)/$SR_{hab+exp=none}$ where $SR_{hab+exp}$ was the species richness predicted from the GAMMS model including both habitat and exposure variables (in this case, minimum hours of exposure) and $SR_{hab+exp=none}$ was species richness predicted from the GAMMS model based on habitat and exposure with exposure set to none. See text for details.

rubble and depth, and significant in relation to low relief limestone and depth (Appendix 4.5; Table A4.5.5). The additional variation accounted for by exposure variables was small. However, if evaluated as an effect size, the percent decrease in species richness as a function of minimum hours of exposure, controlling for calcareous reef and depth, ranges between 10 and 40% when the minimum hours of exposure exceeds 300 (Figure 4.25).

The shoal level analysis based on linear regressions confirmed this pattern. Mean species richness per deployment increased with increasing cover of calcareous reef (adjR2 = 0.74, p=0.0017) and increasing distance from the Montara well head platform (cumulative adjR2=0.83, p=0.08) (Appendix 4.5; Table A 4.5.6). The number of species per deployment decreased by between 5 and 10% as distance from the well decreased below 50 km (Figure 4.26, upper graph).

Variability in total abundance between shoals, and as a function of habitat and exposure

Total abundance per deployment varied by shoal from 77.2 (12.2± SE) individuals at Shoal 25 to 153.4 (21.7± SE) individuals at Eugene McDermott (Appendix 4.5, Table A4.5.4). Overall total abundance varied among shoals (p=0.0010) with inter-shoal variability primarily driven by Eugene McDermott, which differed significantly from Barracuda West (p=0.03), Shoal 25 (p=0.03). All other pairwise comparisons of shoals were insignificant.

GAMMs indicated that between 5% and 14% of the variation in total abundance could be explained by habitat variables (based on $adjR^2$) (Appendix 4.5 Table A4.5.5) with calcareous reef the best predictor of total abundance ($adjR^2$ = 0.14). The addition of exposure variables did not improve model fit (Appendix 4.5; Table A4.5.5) and thus no effect size was estimated. While total abundance was highly variable and no strong patterns could be discerned with habitat at the level of individual deployments, linear regression analysis at the level of shoals suggested that total abundance was positively correlated to the percent cover of sponges (adjR2=0.79; p=0.0008), as estimated from the towed video transects, and negatively correlated to HC concentration (combined adjR2=0.85; p=0.0014) (Appendix 4.5; Table 4.5.6). Moreover, it appears that percentage declines in total abundance were between 10 and 30% when [HC] was greater than 0.14 μg/g (Figure 4.24).

(I) Variability in mean length between shoals, and as a function of habitat and exposure

Mean length of fishes per deployment varied among shoals from 283 mm (10.7± SE) at Heywood to 339 mm (17.5± SE) at Vulcan (Appendix 4.5; Table A4.5.4). Overall, mean length varied among shoals (p=0.045) however most pair-wise comparisons between shoals indicated no significant differences, despite variability in habitat. GAMMs indicated that between 6% and 10% of the variation in mean length could be explained by habitat variables (based on $adjR^2$) (Appendix 4.5; Table A4.5.5) with calcareous reef the best predictor of mean length ($adjR^2$ = 0.10; Appendix 4.5; Table A4.5.5). The addition of exposure variables to this model indicated that the effect of distance from uncontrolled release and minimum hours of exposure were significant (p=0.0006 and p=0.023 respectively; Appendix 4.5; Table A4.5.5). The additional variation accounted for by exposure variables appears small and indeed, with respect to the effect size, there is less than a 0.2% change in length as a function of hours of exposure (Figure 4.25). The shoal level analysis based on linear regressions showed a much stronger effect: mean length declined with increasing profile ($adjR^2$ = 0.64, p=0.0058) and increased with increasing sediment hydrocarbon concentration (cumulative $adjR^2$=0.86, p=0.012) (Appendix 4.5; Table A4.5.6). The size of this effect was relatively small with the medium exposure shoals having a less than 2% increase in mean length with increasing sediment hydrocarbon concentration and the high exposure shoals having a 6-12%

increase in mean length (Figure 4.27). The increase in size with proximity to the Montara well head platform can also be observed in the length frequency histograms (Figure 4.28) and the relationship between the median size and distance from Montara well head platform, however the effect appears subtle.

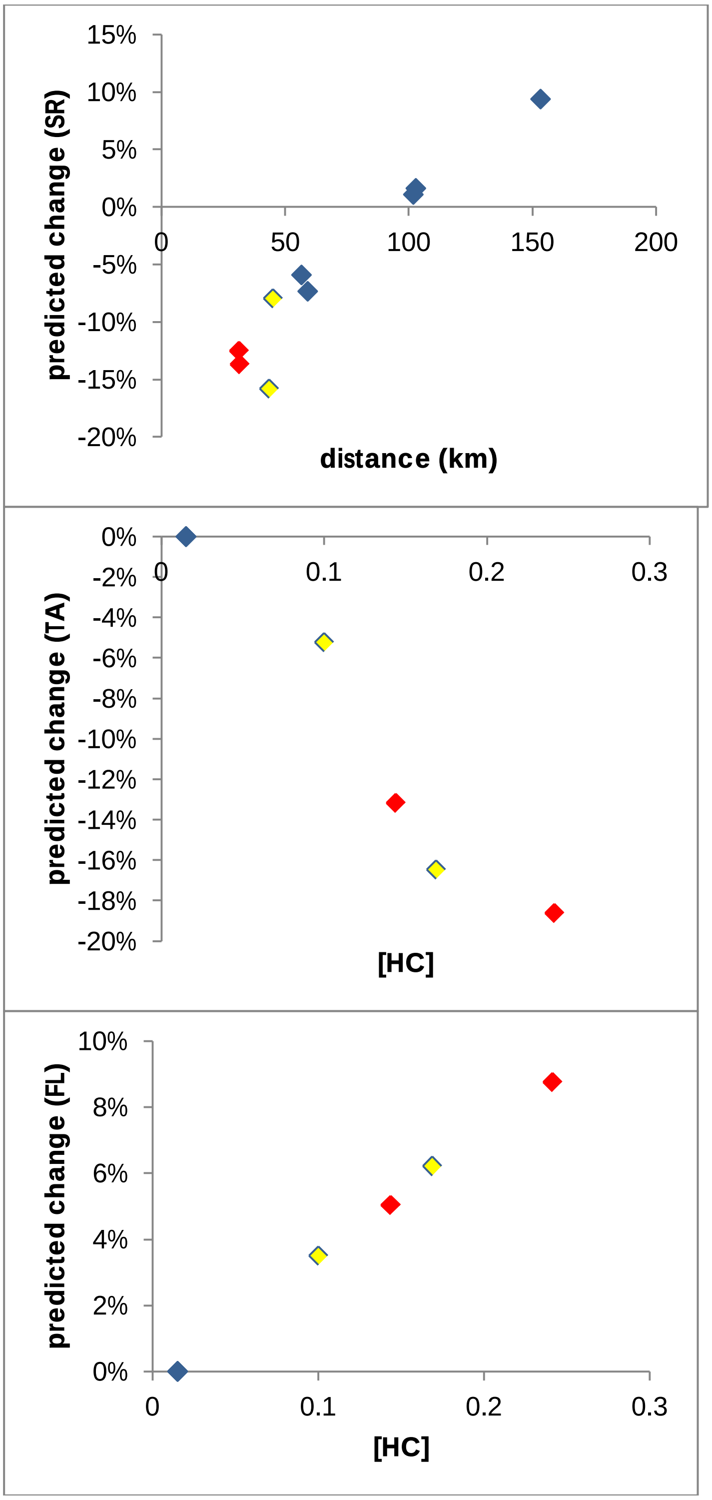

Figure 4.26. Percentage change in (a) species richness (SR) vs distance from MWP (km), (b) total abundance (TA) and sediment hydrocarbon concentration ([HC] and (c) length (FL) and [HC]. Colour of symbols refers to low exposure (blue), medium exposure (yellow) and high exposure (red) sites. Percentage change calculated as per Figure 4.25 As observed [HC] and no [HC] are equivalent for the five lower exposure shoals, the % change is 0 for these five shoals.

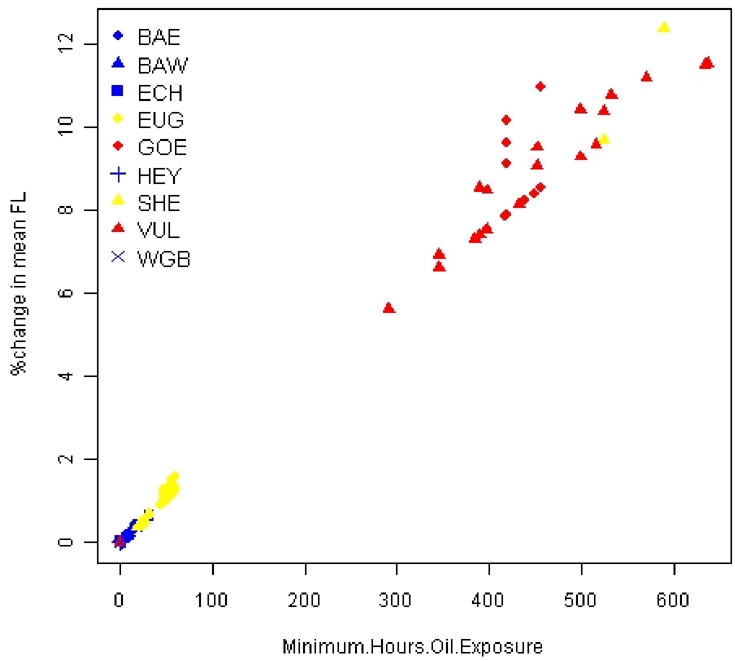

Figure 4.27. Effect size as % of change in mean length (FL) vs distance from the uncontrolled release (distsp). Percentage change calculated as for species richness (Figure 4.25).

(IV) Variability in total biomass between shoals, and as a function of habitat and exposure

Mean total biomass per deployment varied among shoals from 68.1 kg (8.3± SE) at Heywood to 111 kg (14.0± SE) at Barracouta East (Appendix 4.5; Table A4.5.4). Overall biomass varied among shoals (p=0.013) with most pairwise comparisons between shoals indicating no significant differences with the primary exceptions of Goeree and Heywood that differed from Barracuda East, Echuca, Eugene McDermott and Vulcan despite variability in habitat. Approximately 8% of the variation in biomass could be explained by habitat variables (based on adjR^2) (Appendix 4.5; Table 4.5.5). Distance from Montara well head platform was marginally significant (p=0.0793) and its addition increased the adjR^2 to 0.11 (Appendix 4.5; Table A4.5.5). The additional variation accounted for by exposure variables appears small and indeed, the effect size is relatively small, between 6 and 10% for shoals less than 50 km from the Montara well head platform (Figure 4.29). Consistent with this, the shoal level analysis found only weak relationships between biomass and habitat variables (p=0.09; adjR^2<0.06) and no effects of any of the exposure metrics.

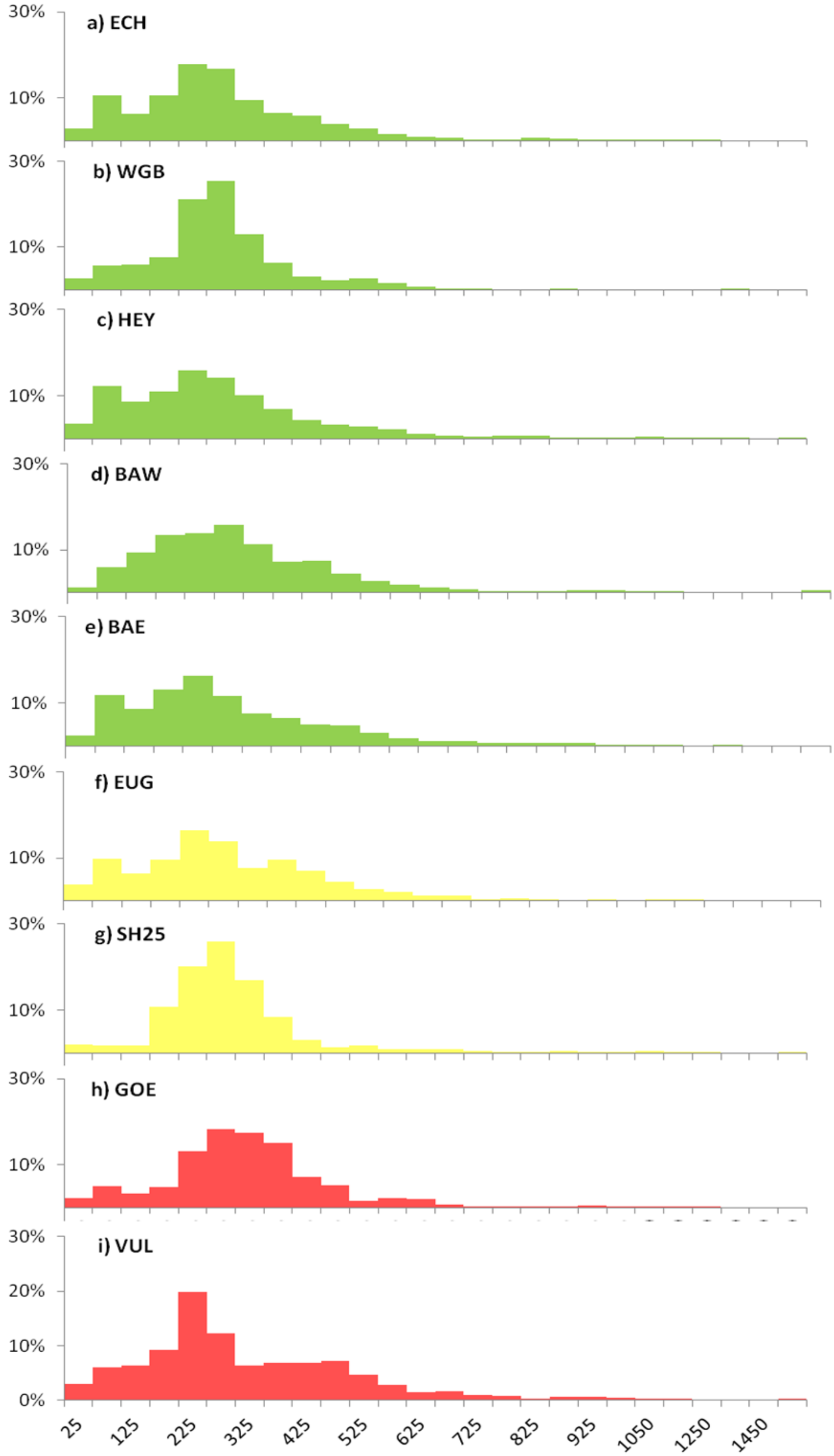

Figure 4.28. (a) Length frequency histograms ordered vertically from shoal most distant to uncontrolled release (ECH) to shoal closest to spill (VUL) and (b) median length as a function of distance from uncontrolled release. Colours relate to exposure category as previously.

4.3.6 Sea snake distribution as a function of habitat and exposure

A total of 117 sea snakes were recorded of which 66 were the olive sea snake, *Aipysurus laevis* (IUCN Least Concern; population decreasing), and four were identified as the ornate sea snake, *Hydrophis ornatus* (IUCN Least Concern; population trend unknown). The remaining 47 could not be reliably identified due the image quality, range, or lack of recognisable markings. Sea snakes were observed on 96 deployments, or 39% of the total of 248 deployments. Of these 96 deployments, a relative abundance of one was observed on 83% (79) deployments with two sea snakes observed on 14 deployments, three sea snakes observed on two deployments and four sea snakes observed during a single deployment.

The total sightings indicated that sea snakes were not absent from "high exposure" shoals and neither analytical approach found a spatial gradient in abundance related to distance from the well. ABT models showed that BRUVS in depths shallower than 30 m had higher probability than average of encountering *A. laevis*. Models for *A. laevis* showed the influence of increasing distance from the Montara well head platform (spilldist) was about a 2% *decrease*, above average, in probability of a sighting across the range of values (Appendix 4.3, Figure A4.3.1). For the unidentified sea snakes pooled into one "taxa", the influence of "spilldist" was in the opposite direction – but only about a 2% increase, above average (Appendix 4.3, Figure A4.3.2).

Sea snakes were not uniformly distributed across the deployments or shoals (Appendix 4.5; Table A4.5.7). Logistic regression indicated that, at the scale of deployments, the presence / absence of sea snakes was negatively related to depth (p=0.0000004), algae (p=0.00461) and longitude (p=0.00256) such that sea snakes were less likely to be present as depth and algae increase and on more eastern sites closer to the uncontrolled release. The addition of each variable sequentially reduced the AIC by at least five with the final model having an AIC of 266. The AIC associated with the intercept only model was 333. The addition of minimum hours of exposure was marginally significant (p=0.078), but was excluded as it is moderately confounded with longitude (r=0.47) (Appendix 4.5; Table A4.5.3) and was not significant on its own.

At a shoal level, the number of sea snakes per deployment ranged from a high of 0.92 at Vulcan to 0.04 at Shoal 25. Linear regression indicated that sea snake abundance in terms of mean numbers observed per deployment per shoal, did not vary with overall fish species richness nor with total fish abundance but was inversely correlated to mean depth of the shoal (p=0.047, n=9; Figure 4.30) and inversely correlated to algal cover (p = 0.0008 Figure 4.30), consistent with the patterns seen in the logistic regressions. Mean number of sea snakes was also negatively correlated with soft coral and positively correlated with rubble (Figure 4.30). There was no effect of exposure or longitude on any of these relationships..

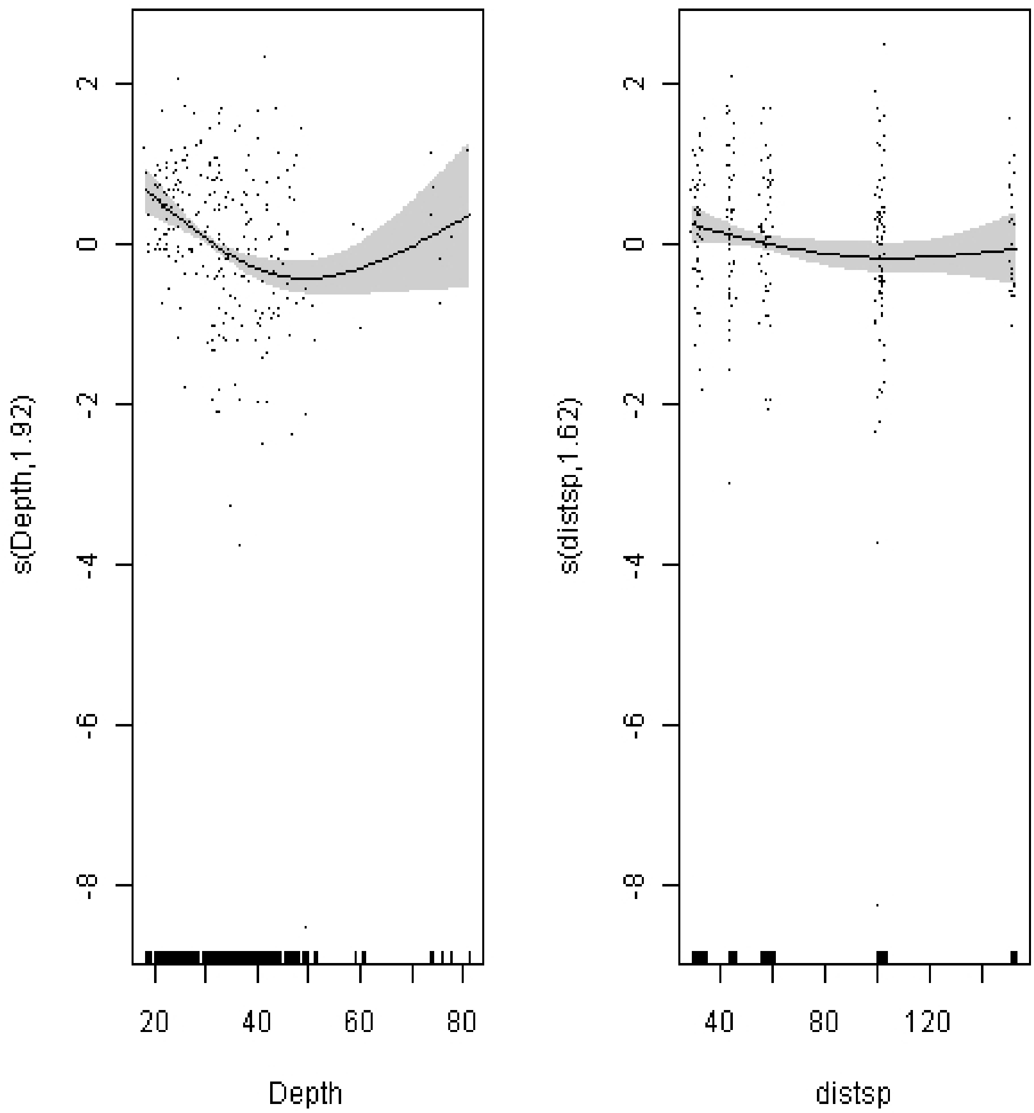

Figure 4.29 GAMMS of biomass (B) vs depth and distance from the uncontrolled release (distsp).

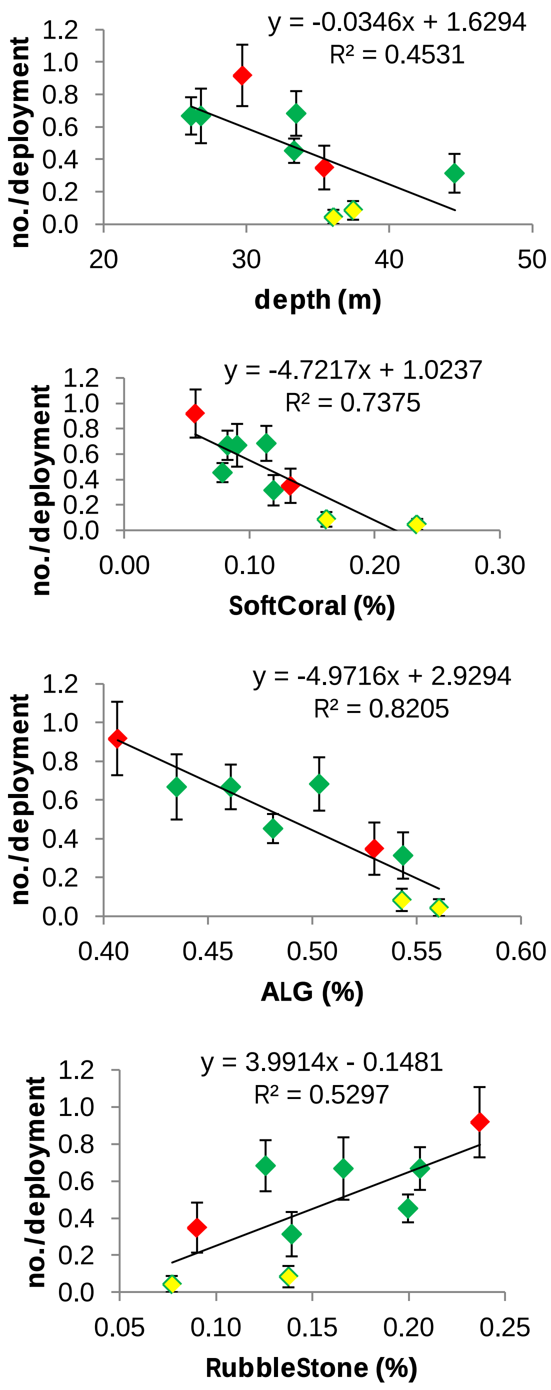

Figure 4.30. Regressions of the mean number of sea snakes per deployment (±SE) vs habitat. Colour of symbols as previously.

4.4 Conclusions

The results mark the fish fauna of these submerged shoals as biologically rich. Median fish abundance and fish species richness on the shoals were between 1.25 to 3 times higher than for equivalent banks, shoals and reef edges in the Great Barrier Reef Marine Park (GBRMP). This is possibly because the GBRMP shoals are located within the confines (lagoon) of a barrier reef, and not subject to the oceanic influences and associated processes experienced by the shoals in this study (see Cappo et al. 2011). The shoals supported many species known from the emergent reefs in the region, including Ashmore, Cartier, Scott and Seringapatam Reefs (e.g. Heyward et al. 1997; Heyward et al. 2011).

Both types of statistical analyses (regression tree approaches and GAMMS/linear models) provided evidence for a spatial gradient in diversity, which tended to decrease slightly towards the Montara well head platform. However, the regression tree approach focussed on illustrating interactions amongst all explanatory covariates and finding models with the lowest prediction error across numerous simulations, whereas the other, more common approach focussed on main effects and reducing error in step-wise building of models.

The regression tree approaches found all indices of oil exposure to be weak or negligible in predicting species richness, total abundance, community structure and occurrence of individual, common species. Nonetheless, the GAMMS and linear regression analyses found more explicit evidence for gradient trends in community structure in relation to exposure metrics, having accounted for the spatial correlation/structure in the model, i.e. correlation among observations on the same sampling unit (here shoal). These latter analyses pointed to a decline in species richness and abundance in some fish groups on shoals closest to the well head. Acknowledging that both are models, with various assumptions, these two analytical assessments could be viewed as indicative of the low and high ends of probability for the Montara uncontrolled release as a contributor to the observed spatial patterns. Below, we discuss in detail the results of each modelling approach in terms of habitats and exposure.

4.4.1 Fish Distributions

Reviews indicate that fish communities on tropical shelves can be structured by biogeography, regional sources of upwelling and runoff, thermoclines, mud content of sediments, topographic complexity, depth, latitude, ontogenetic migrations and species replacements through the effects of fishing (e.g. Longhurst 2007, Longhurst and Pauly 1987; Lowe-McConnell 1987, Sainsbury et al. 1997, Letourneur et al. 1998; Williams and Bax 2001). In the case of these nine shoals, much of the habitat and fauna was similar to those found on coral reefs, so many of the paradigms about coral reef fish – habitat associations are relevant to interpreting the results presented here.

The multivariate regression tree analysis was used to simultaneously examine the response of the abundances of a suite of common species to all environmental covariates, identify key splitting variables that produced similar groupings, and identify key indicator species for each grouping (assemblage). The best tree, with the lowest prediction error, recognised six fish communities amongst the shoals, based on depth, the amount of reefal substrata in the BRUVS field of view, and the size (area) of the shoal from which each sample was taken. Schematic maps of the communities showed the largest shoals (such as Heywood) had the most communities, whilst the smallest shoals sometimes were inhabited by only one (Shoal 25) or two communities (Wave Governor Bank); this is consistent with the theory of species - area relationships (Lomolino and Weiser 2001). Shoal tops had more diversity in the membership of BRUVS sites amongst community types compared to the shoal rims. Species accumulation curves for these six assemblages did not reach an asymptote, indicating

some under-sampling of true fish biodiversity in the region. However such curve shapes are common for BRUVS analyses (Cappo et al. 2007a), because BRUVS sample demersal, semi-demersal, and pelagic species. Many of the pelagic and semi-demersal species are large, mobile and relatively rare and complement a "core" demersal, species set (Magurran & Henderson 2003).

The fish communities were significantly related to habitat, although the strength of these relationships varied. Many common species used a variety of habitats. The cover of reefal substrata in the field of view, depth, and the direction of the slope on which the BRUVS were set (aspect) accounted for most of the influence on species richness. In terms of fish abundance, the aspect, amounts of bare seafloor and reefal substrata in the field of view accounted for over 52% of the influence in ABT univariate models. The coverage of the seafloor near the bait by calcareous reef was identified as an important habitat variable in this analysis. This was expected given the affiliations of the major faunal families with coral reefs in the Indo-Pacific. Models of presence/absence of the 54 most prevalent species in relation to all the environmental covariates and uncontrolled release indices found that the top five explanatory variables were aspect, depth and coverage of calcareous reef, followed by latitude and longitude. These models avoided the problems known to occur in analysing fish counts, such as bias in counting by observers and over-dispersion of the count data.

That aspect was a major driver of fish occurrence is consistent with knowledge of reef trophodynamics (Polunin 1996). Sites sloping toward the north and east had lower than average probability of encountering the large and small planktivores, and some of their predators, and the converse was true for southward and westward sloping sites. It is possible these southern slopes are the locations where food-rich currents from waves, tides and episodic upwellings occur, bringing food for planktivores, which in turn attract carnivores.

Similar to the ABT analysis, the GAMMS and regression analyses found that at both the level of deployments or shoal, all univariate metrics of the fish community were significantly related to habitat, although the strength of these relationships varied. At the level of deployments, the pattern between species richness and habitat was reasonably strong while the habitat relationships for total abundance, size and biomass were more variable, albeit still significant. At the level of shoals, the relationships between fish community metrics and habitat were very strong for species richness, total abundance and length, with no strong relationships between biomass and habitat.

The observed fish-habitat relationships were similar to relationships reported in the literature, although significant variation exists across studies (Gratwicke and Speight 2005). Species richness increased with reef structure, here represented as the percent cover of calcareous reef, as in a number of other studies (Gratwicke and Speight 2005; Friedlander and Parrish 1998) and generally declined with depth (see Brokovich et al. 2008; Garcia-Sais 2010). Total abundance increased with the percentage cover of sponge and calcareous reef and decreased with increasing depth (see Garcia-Sais 2010; Friedlander and Parrish 1997, Gratwicke and Speight 2005). The mean length of fish decreased as profile and calcareous reef increased, suggesting that smaller fish were more typical of higher relief reef areas, a pattern also suggested by Friedlander and Parrish (1998). While no relationship between biomass and habitat could be found at the level of shoals, when analysed using BRUVS data at individual deployment level, biomass showed a similar pattern to species richness and total abundance, declining with depth with a slight increase at the deeper deployments. Such patterns in biomass were also observed for depth by Knudby et al (2010). That fish community/ habitat relationships were generally consistent with other studies, and were consistent in direction across the two scales of analyses (shoal and deployment), suggests

that these models provided a reasonable basis for assessing potential impacts of exposure on the fish assemblage.

Sea snakes showed strong relationships with depth and habitat. Studies elsewhere also showed preferences for coral/rubble areas (Shine et al. 2003; Burns and Heatwole 1998) and small home ranges on the order of 1500 m^2 (Burns and Heatwole 1998).

4.4.2 Potential for effects of oil exposure

There were three indices of potential exposure to hydrocarbons used in our spatial analysis of fish communities on the shoals. These metrics included distance from the Montara well head platform and hours of exposure to the modelled Montara plume, while the third, adjusted hydrocarbon concentrations in sediments, was also used because there was demonstrated spatial variation between shoal locations even though this variable could not be directly linked to the uncontrolled release.

The regression tree analyses found that the effect of the uncontrolled release was weak or negligible. These analyses ranked the distance from the Montara well head platform 9th, the time of oil exposure 21st, and the sediment hydrocarbon concentration 30th in influencing species richness, thus far less influential than depth, aspect and coverage by reefal substrata. In terms of predicting total (pooled) fish abundance, these ranks were even lower (13th, 23rd, 37th). On average, across the 54 most prevalent species sighted on the BRUVS, the rank of influence in predicting presence/absence of the indices of oil exposure was 6th for distance from the well head platform, 19th for time of exposure to the uncontrolled release, and only 38th for the sediment hydrocarbon exposure. The highest influence of any of the three exposure indices was only 1.34% for richness and 1.26% for total fish abundance.

Individual ABT models were used to predict the occurrence of 54 most common species at each BRUVS site in terms of the 41 explanatory covariates. The distance from the Montara well head platform was the only indicator of the effect of the uncontrolled release, and it had an average influence of only 2.8% on predicting the occurrence of the individual species, whereas the influences were much higher for aspect (25.2%), depth (14.4%), %reefal substrata (6.7%), latitudinal position (6.7%) and longitudinal position (5.4%). The greatest individual influence was only 5.7% for predicting the presence or absence of the emperor *Lethrinus atkinsoni*. For this reef-associated mobile emperor the best model predicted that the probability of occurrence was actually 10% higher than average closest to the Montara well head platform, on Vulcan shoal. From these analyses we concluded that any effects of these indices of oil exposure on the structure of fish faunas were weak or negligible.

The GAMM and regression approach, however, found that there was potentially an effect of uncontrolled hydrocarbon release on four attributes of fish communities when both scales of analyses were considered and based on a weight of evidence approach (Gerrodette 2011). Controlling for habitat, species richness declined with decreasing distance to the Montara well head platform, with an increasing exposure in terms of minimum hours. Both scales of analyses indicated that the percent decrease in mean species richness at distances less than 50 km was approximately 10-15%. Total abundance also decreased with increasing concentration of hydrocarbons in the sediments and decreasing distance to the Montara well head platform; at hydrocarbon concentrations greater than 0.1 µg/g, total abundance decreased by between 6 and 20%. These effect sizes were surprisingly large given the marginal nature of the statistical significance, but suggest they may still be of ecological significance (see Fidler et al. 2006; Gerrodette 2011). Mean length of fish increased with increasing hydrocarbon concentration and increases in the minimum number of hours of exposure, suggesting that smaller fish declined in abundance with increasing exposure. Despite the greater significance of the exposure variables in the models, the effect on size

was somewhat smaller, representing between a 3% and 10% increase in mean length at hydrocarbon concentrations greater than 0.1 µg/g. This pattern was repeated with biomass at the level of deployments, reflecting the smaller mean length of fish at greater distances from the Montara well head platform. It should be noted that measured oil concentrations in sediments around the shoals reflected elevated concentration within approximately 50 km of the Montara well head platform, albeit 18 months after the uncontrolled release at levels unlikely to cause biological effect, while shoal sites further away had very low or non-detectable levels. Consequently, the seabed samples reflect a stepwise decrease away from the Montara well head platform, as opposed to the more gradient like exposure model for surface hydrocarbons. It should also be noted that there are other sources of hydrocarbons in this region (see Chapter 2) and that the spatial patterns of hydrocarbon presence in sediments appear to be complex.

There is a rapid diminution in net primary production with depth down coral reef slopes, and Polunin (1996) reported that this is generally accompanied by a down-slope shift toward dominance of larger planktivorous and piscivorous fish. Thus any coarse assessment of the effect of oil exposure on length compositions might be confounded by the depth at which measurements were made, and what species were measured on each shoal (e.g. Smith et al. 2002). However, the shoals closest to the uncontrolled release had mean depths comparable to, or shallower, than other shoals, so depth alone cannot be invoked as an explanation for the increase in fish length in relation to increasing hydrocarbon concentrations.

The few down-slope BRUVS surveys to date on the Sahul/Karmt shoals and Scott Reef Lagoon showed a replacement of diverse small, pomacentrid (damselfish) planktivores in the shallows (<=20m) to small, diverse *Pentapodus* (whiptail) omnivores, schooling labrid (wrasses) planktivores and anthiid (fairy basslets) planktivores at 50-60 m (Heyward and Cappo, unpublished data). However, it is unknown if small lengths are conserved in this species replacement, because no measurements were made from the (single camera) BRUVS. Those surveys examined a larger depth gradient than is present in this study. Hence the specific explanation of an increase in fish length in correlation with increasing hydrocarbon concentrations is unclear.

Why would a decrease in species richness and abundance and an increase in mean size be consistent with exposure to hydrocarbons and dispersants? This is not a trivial question and relies largely on theory given the dearth of appropriate before/after data associated with oil spills (Teale and Howarth 1984). Moreover, much of the literature has focused on development of bioassays and the detection of hydrocarbons on select indicator species rather than assessing ecological impacts at the community level. There also has been significantly more work completed on non-mobile benthos rather than mobile fish, which are more difficult to study.

Theoretically, sensitivity to hydrocarbons and dispersants is a function of the following:

(1) timing of exposure –significant impact can be expected during spawning or recruitment periods when eggs, larvae and new recruits are vulnerable to exposure
(2) duration of exposure – greater lengths of exposure may increase impacts
(3) mobility – species with low mobility are unable to avoid the spill may be affected more than species with avoidance capabilities (Volgelbein and Under 2006)
(4) feeding modes – species that increase their exposure (i.e. species in significant contact with the contaminated sediments (Kennicutt et al. 1991) or preying on contaminated zooplankton (Teale and Howarth 1984) may be more sensitive

(5) body size – given the impacts of hydrocarbon exposure on gills, skin and liver (Giari et al. 2012; Cohen et al. 2001), smaller species and smaller individuals within species are more vulnerable to exposure because they have a higher surface area to volume relationship, they have higher gill surface area per unit body weight (Pauly 1998), and respire more quickly (Peters 1986).

Thus, species richness might be expected to decline with exposure to hydrocarbons where some species are relatively sensitive to hydrocarbons and/or dispersants due to low mobility, vulnerable feeding modes or small size, compounded by exposure at reproductively sensitive periods. Such declines might be offset by the arrival of more tolerant species, but the time frame between the uncontrolled release and the study (~17 months) and the relative isolation of the shoals means such arrivals would likely be as larvae and it is unclear how many would have reached sufficient size to be detectable on the video systems within this time. Even if new species had arrived, the net trend in species richness was negative. Our results do not necessarily indicate extirpation, but rather a reduction in abundance such that the probability of observation is greatly reduced.

Total abundance is often correlated with species richness (Dornelas et al. 2011), as was the case in our study ($p=0.029$; $n=9$), and for this reason it was not surprising that abundance showed similar declines to species richness. Additionally, within-species variability in sensitivity to hydrocarbons may also lead to declines in the overall number of animals present due to losses of relatively sensitive individuals.

That length increased with increasing exposure suggests that smaller individuals were more sensitive to the exposure than larger individuals. A number of mechanisms related to body size are possible given that body size strongly influences an organism's interaction with its environment (Peters 1986; Pauly 2005). The surface area to volume ratio increases with decreasing body size. If hydrocarbon toxicity is mediated through skin, smaller fish will absorb more toxins than larger fish per unit body weight. Smaller fish also have larger gill surfaces per unit body weight than large fish (Pauly 2005). As gill function is significantly impacted by exposure to hydrocarbons and dispersants (Duarte et al. 2010; Al Hassan et al. 2000), smaller animals may thus be more vulnerable. Metabolism is also faster in smaller fish (Pauly 2005), which may increase vulnerability to stress associated with hydrocarbon exposure. It was unexpected that total biomass per deployment would increase with exposure and this result must be treated with caution as the biomass-habitat relationship detected by GAMMS was weak. While mean biomass might increase due to the absence of smaller fish, the observed effect implies an absolute increase in biomass and the ecological reasons for this are unclear.

Body size also influences behavior and feeding mode. Smaller fish tend to have smaller home ranges (Peters 1985) than larger fish, reflecting lower absolute swimming speeds (Peters 1985) as well as the need to minimize predation risk. Oil, when it settles on a reef, does so in patches both as it moves through the water column and when it reaches the benthos. Larger fish may be more adept at avoiding direct exposure by an ability to avoid patches both in the water column and on the benthos. Herbivores, detritivores and planktivores are typically smaller than piscivores (www.fishbase.org). In their review of major oil spills for which data is availability, Teal and Howarth (1984) note that oil is typically transported to the seabed with likely deleterious effects on benthic-dwelling species, which would include, for instance, turf cultivating pomacentrids and other small species. They also state that, where data were collected, zooplankton were typically contaminated with oil droplets, thus creating a risk for zooplanktivores, many of which are relatively small species.

Due to a lack of pre-Montara baselines, we adopted a gradient approach to the study in relation to hydrocarbon exposure. Fish communities on tropical shelves can be structured

by numerous factors (eg; Longhurst 2007; Longhurst and Pauly 1987; Lowe-McConnell 1987; Sainsbury et al. 1997; Letourneur et al. 1998; Williams and Bax 2001) that we cannot discount as influencing the spatial patterns in diversity, abundance and size observed. For this reason, a key question was whether the observed patterns in the fish assemblage were simply a function of shelf position. It is possible that species richness and total abundance increase naturally in a west-south-westerly direction and that mean size decreases naturally along this same gradient, but there is a lack of any published data showing such a trend for this region.

Strong cross-shelf gradients in fish species richness are expected on tropical shelves at the scale of 10's of kilometres (or less, depending on shelf width) and have been reported for the Great Barrier Reef (GBR) (e.g. Williams 1991, Gust et al. 2001, Mellin et al. 2010), New Caledonia (Letourneur et al. 1998) and for tropical soft-bottom fish faunas in south-east Asia (Garces et al. 2006). However, it is yet to be demonstrated that similar processes operate on these North-West shoals and if so, in which direction such gradients may lie.

Latitudinal changes in species richness might be expected to be small among the shoals surveyed by our study (Brayard et al. 2005; Gray 2001; Ormond & Roberts 1997), given the results of previous studies of reefal and inter-reefal fish faunas in tropical Australia. These show that latitudinal changes in fish communities are typically far smaller over equivalent spatial scales than those occurring on a cross-shelf basis. For example, although there are strong gradients in alpha (within habitat) diversity of eastern Australian coral reef fishes, which decline at the scale of the entire GBR from more than 2,000 species in the far north to about 1,000 at the southern extent of the reef (Ormond & Roberts 1997), Williams (1991) showed that latitudinal variation in reef fish assemblages over nine degrees of latitude on the GBR was far outweighed by the influence of position of reefs across the shelf at the much smaller scales of kilometers to tens of kilometers, and it is this latter spatial scale that is relevant to our study.

Although the distance offshore of a reef is thought to be a significant predictor in models of species richness (Mellin et al. 2010), Fabricius et al. (2005) show clearly that the shoal position as a proportion of total shelf width is a better predictor of cross-shelf gradients in reef faunas. With approximately 120 km between the most distant shoals (Vulcan and Echuca), Mellin et al.'s (2010) model would predict a strong cross-shelf gradient in richness once variation in habitat had been accounted for. However, the North-West Shelf is relatively wide and the 9 shoals we sampled were not close to the coast, so there were no obvious inshore extremes of turbidity, wave energy at the seabed and freshwater input that might have been expected to produce a gradient in species richness or community composition towards the inshore.

Much less is known about oceanic influences on fish community structure at the offshore edge of the shelf and these may well be present in the study area. Further north, tidally-trapped internal waves, episodic upwelling and the "Indonesian Through-Flow" occurring at the outer edge of the shelf could be expected to produce cross-shelf gradients in environmental conditions for fishes. Thus, the cross-shelf position of a shoal cannot be disregarded as a factor potentially confounding any signals of the uncontrolled release in fish assemblages. Better knowledge of local oceanographic processes surrounding the shoals could improve the predictive capability of models of fish community structure. It is important to note, however, that it is very unlikely that the results of the GAMMS and regression analyses were confounded by some combination of exposure metrics and habitat, as neither minimum hours nor distance from the Montara well head platform were correlated with any of the habitat variables that explained community metrics. Consequently, while the shoals support abundant and diverse fish communities, predominantly influenced by the natural attributes of each location, without pre-spill

baselines we cannot exclude influence from the spill in contributing to the subtle spatial patterns observed. Independent surveys have reported a hydrocarbon biomarker signal in at least four larger fish species in the region which attenuates with distance from the Montara WHP, (Gagnon and Rawson, 2011), demonstrating at least some level of hydrocarbon interaction with both demersal and pelagic species.

Although a small number of sea snakes were found dead in the area of the Montara well head platform during the uncontrolled release, with biopsy indicating exposure though either ingestion of contaminated prey or direct inhalation (Gagnon and Rawson, 2010), there was no data on abundance of sea snakes on these shoals prior to the Montara release. The efficiency and accuracy of BRUVS as a tool to sample populations of sea snakes is also unknown, although they are a ubiquitous component of tropical BRUVS datasets, albeit in low numbers (e.g. Cappo et al. 2004, 2007a, 2011). Consequently, while no gradient effect was found, it is impossible to know if diversity or numbers have been substantially reduced in relation to the uncontrolled release. The data do show a variety of seasnakes were present on shoals close to the Montara well head platform, but we cannot determine if these were new immigrants, or resident at the time of the uncontrolled release, or diminished in numbers by the uncontrolled release of oil.

The shoals sampled in this study were highly diverse systems set within complex oceanography. In the absence of a baseline for the region, it is not possible to state that there has been no effect of the uncontrolled release on the fish community; conversely the release may not be the cause of any of the observed patterns, which are derived from only a snapshot sample of the status of fish on the shoals. If the uncontrolled release was the cause of the observed spatial patterns, it might be expected that species richness, total abundance and size will recover in a 2-5 year period, since many of the smaller reef fishes are relatively short–lived and noting that Barber et al (1995) found an apparent recovery of fishes after three years in relation to the Exxon Valdez oil spill. Follow-up studies might also address the possibility that species that were reproductively active at the time of the release and whose larvae were affected might be have gaps in year-classes corresponding to the timing of the release. Future changes in fish communities of these shoals warrant monitoring and the data captured from the nine shoals in the Montara study provide a foundation for an excellent regional baseline into the future.

4.5 Recommendations

In light of the uncertainty around whether the Montara uncontrolled release affected the fish assemblage, additional monitoring should be undertaken at the surveyed shoals, and other more remote shoals, in order to determine if the observed patterns remain consistent with possible influence from the Montara uncontrolled release. Such targeted monitoring would need to test:

(1) the existence of the observed cross shelf pattern in species richness, total abundance and size across a larger spatial scale not confo unded by the uncontrolled release;

(2) for a decrease in the effect size of exposure metrics on exposed shoals (c.f. Barber et al. 1995), with respect to species richness, total abundance and size through time.

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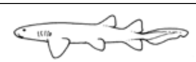
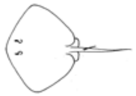
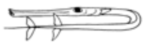
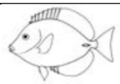
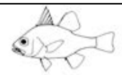
Appendix 4.1 ABT analysis: species by shoal matrix, showing total counts (sum *MaxN*) of each "taxa" used in the analyses. Shoals are ranked by exposure category from left (low) to right (high).

Order/family	Genus	species	WGB	ECH	BAW	BAE	HEY	SH25	EUG	VUL	GOE
Carcharhiniformes											
Carcharhinidae		**Requiem (whaler) sharks**									
	Carcharhinus	*albimarginatus*	2	1	0	0	2	10	1	3	0
	Carcharhinus	*amblyrhynchos*	21	31	27	43	41	35	20	40	16
	Galeocerdo	*cuvier*	0	0	0	0	0	0	0	1	0
	Loxodon	*macrorhinus*	0	0	0	0	1	1	2	0	0
	Negaprion	*acutidens*	0	0	3	1	2	1	3	1	0
	Triaenodon	*obesus*	5	23	20	38	35	1	22	18	12
Sphyrnidae		**Hammerhead sharks**									
	Sphyrna	*mokarran*	0	0	2	1	3	3	0	3	2
Triakidae		**Weasel sharks**									
	Hemitriakis	*falcata*	0	0	0	0	0	0	12	0	0
Orectolobiformes											
Ginglymostomatidae		**Nurse sharks**									
	Nebrius	*ferrugineus*	0	0	0	1	1	1	0	0	0
Rajiformes											

Order/family	Genus	species	WGB	ECH	BAW	BAE	HEY	SH25	EUG	VUL	GOE
Rhinidae		**Shark rays**									
	Rhina	*ancylostoma*	0	2	0	0	0	0	0	1	0
Myliobatiformes											
Dasyatidae		**Stingrays and eagle rays**									
	Dasyatis	*kuhlii*	5	1	8	9	3	6	3	6	3
	Himantura	*fai*	0	0	0	0	0	0	0	0	1
	Taeniura	*lymma*	1	2	6	8	0	0	1	2	3
	Taeniura	*meyeni*	0	0	0	0	2	0	0	1	2
	Aetobatus	*narinari*	1	0	0	0	0	0	1	0	0
Anguilliformes											
Congridae		**Conger and Moray eels**									
	unk	*sp1*	0	0	0	0	80	0	0	0	0
Muraenidae	*Gymnothorax*	*all*	2	1	0	0	2	1	2	0	1
	Gymnothorax	*favagineus*	0	0	0	0	1	0	0	0	0
	Gymnothorax	*fimbriatus*	0	1	0	0	0	0	0	0	0
	Gymnothorax	*flavimarginatus*	0	1	0	0	0	0	2	0	1
	Gymnothorax	*javanicus*	0	0	0	0	1	0	0	0	0
	Gymnothorax	*undulatus*	1	0	0	0	1	0	0	0	1
Beryciformes											

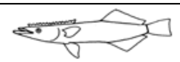
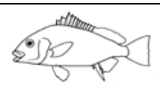
Order/family	Genus	species	WGB	ECH	BAW	BAE	HEY	SH25	EUG	VUL	GOE
Holocentridae		**Squirrelfishes**									
	Myripristis	*botche*	0	0	0	0	2	0	0	0	0
	Myripristis	*sp1*	0	1	0	0	0	0	0	0	0
	Sargocentron	*caudimaculatum*	0	5	0	1	1	0	0	0	0
Gasterosteiformes											
Fistulariidae		**Flutemouths**									
	Fistularia	*commersonii*	5	1	1	6	2	1	2	2	1
Scorpaeniformes											
Pteroidae		**Scorpionfish**									
	Pterois	*sp1*	0	0	0	0	0	0	1	0	0
Perciformes											
Acanthuridae		**Surgeonfish**									
	Acanthurus	*dussumieri*	1	4	0	0	5	0	0	0	1
	Acanthurus	*grammoptilus*	4	98	4	10	103	18	127	72	6
	Acanthurus	*leucocheilus*	5	6	4	12	23	0	7	5	4
	Acanthurus	*mata*	1	4	0	1	16	18	1	15	0
	Acanthurus	*nigricans*	0	2	4	2	2	0	4	2	2
	Acanthurus	*olivaceus*	4	27	14	24	73	0	33	24	1
	Acanthurus	*pyroferus*	0	1	0	4	5	0	0	2	1

Order/family	Genus	species	WGB	ECH	BAW	BAE	HEY	SH25	EUG	VUL	GOE
	Acanthurus	*sp1*	0	1	0	0	0	0	0	0	0
	Acanthurus	*thompsoni*	0	0	2	1	3	0	0	2	0
	Acanthurus	*xanthopterus*	0	3	0	6	27	54	0	2	0
	Ctenochaetus	*binotatus*	0	0	0	0	2	0	0	0	0
	Ctenochaetus	*striatus*	0	5	9	23	7	0	11	11	2
	Naso	*annulatus*	0	0	0	1	8	1	0	1	0
	Naso	*brachycentron*	0	7	2	6	19	2	1	6	6
	Naso	*brevirostris*	4	27	6	7	37	9	22	3	50
	Naso	*caesius*	0	1	0	6	4	0	0	1	0
	Naso	*fageni*	0	2	0	0	1	0	0	0	0
	Naso	*hexacanthus*	502	144	113	87	60	7	134	70	19
	Naso	*lituratus*	0	25	1	9	13	0	12	4	5
	Naso	*lopezi*	1	0	0	99	2	1	2	0	5
	Naso	*mcdadei*	0	0	0	0	0	1	0	0	0
	Naso	*minor*	0	0	0	1	0	8	0	0	1
	Naso	*sp1*	36	0	0	0	1	0	0	0	0
	Naso	*thynnoides*	0	0	0	0	2	0	0	0	41
	Naso	*tonganus*	0	0	0	1	1	0	0	2	0
	Naso	*unicornis*	0	4	1	1	1	0	2	0	0
	Naso	*vlamingii*	3	14	4	16	13	9	11	7	6
	unk	*sp1*	0	0	0	0	0	0	50	0	0
	Zebrasoma	*scopas*	0	0	1	1	0	0	1	0	0
	Zebrasoma	*veliferum*	0	0	0	0	2	0	1	0	0

Order/family	Genus	species	WGB	ECH	BAW	BAE	HEY	SH25	EUG	VUL	GOE
Apogonidae		**Cardinalfish**									
	unk	*all*	0	0	0	0	0	0	1	1	0
Blenniidae		**Blennies**									
	Aspidontus	*dussumieri*	0	6	0	0	1	0	1	0	0
	Aspidontus	*taeniatus*	0	0	0	2	0	0	0	0	0
	Plagiotremus	*tapeinosoma*	0	0	0	0	0	0	0	0	1
	unk	*sp1*	0	6	0	0	0	0	2	1	0
Caesionidae		**Fusiliers**									
	Caesio	*cuning*	0	31	0	0	47	20	0	0	95
	Caesio	*lunaris*	1	0	0	31	0	0	0	0	0
	Caesio	*teres*	40	70	0	0	11	33	119	8	6
	Pterocaesio	*digramma*	1	20	60	93	71	21	0	39	0
	Pterocaesio	*marri*	0	0	0	0	0	0	0	0	1
	Pterocaesio	*pisang*	0	13	0	0	400	0	100	0	0
	Pterocaesio	*sp1*	0	0	0	1	0	0	0	27	0
	Pterocaesio	*sp2*	0	0	0	0	0	0	1	0	0
	Pterocaesio	*tile*	0	30	0	83	0	0	0	0	0
Callionymidae		**Stinkfishes**									
	unk	*sp1*	0	0	0	0	1	0	0	0	0

Order/family	Genus	species	WGB	ECH	BAW	BAE	HEY	SH25	EUG	VUL	GOE
Carangidae		**Trevallies**									
	Alepes	*vari*	19	148	0	120	240	6	270	63	10
	Atule	*mate*	0	186	0	0	2	89	144	61	1
	Carangoides	*coeruleopinnatus*	2	0	0	0	7	7	0	1	3
	Carangoides	*ferdau*	0	2	0	1	14	3	2	5	6
	Carangoides	*fulvoguttatus*	0	18	0	1	36	5	4	1	5
	Carangoides	*gymnostethus*	0	9	21	11	53	81	45	53	38
	Carangoides	*oblongus*	0	1	0	0	1	0	0	0	0
	Carangoides	*orthogrammus*	23	9	59	68	36	1	11	48	29
	Carangoides	*plagiotaenia*	1	0	3	2	11	2	8	10	2
	Caranx	*ignobilis*	0	4	5	6	4	0	8	3	0
	Caranx	*lugubris*	0	0	0	0	0	1	0	0	0
	Caranx	*melampygus*	15	57	23	40	71	0	31	29	29
	Caranx	*sexfasciatus*	17	0	80	50	0	1	1	1	12
	Decapterus	*russelli*	0	0	0	0	0	1	0	0	0
	Decapterus	*sp1*	20	0	0	0	270	4	1	0	0
	Elagatis	*bipinnulata*	15	34	1	97	34	12	64	59	18
	Gnathanodon	*speciosus*	0	0	0	0	8	0	1	0	0
	Scomberoides	*tol*	0	2	1	0	3	0	13	1	0
	Seriola	*dumerili*	0	0	0	1	0	0	0	0	0
	Seriola	*lalandi*	0	1	0	0	0	0	0	0	0
	unk	*all*	40	0	1	0	1	0	0	0	0

Order/family	Genus	species	WGB	ECH	BAW	BAE	HEY	SH25	EUG	VUL	GOE
Chaetodontidae		**Butterflyfishes**									
	Chaetodon	*adiergastos*	0	4	0	0	3	1	2	0	0
	Chaetodon	*auriga*	2	7	2	1	9	1	2	0	2
	Chaetodon	*baronessa*	0	0	0	1	1	0	3	0	1
	Chaetodon	*bennetti*	1	0	1	0	0	0	0	0	0
	Chaetodon	*ephippium*	1	0	0	2	0	0	0	0	0
	Chaetodon	*kleinii*	2	10	5	21	19	0	4	7	2
	Chaetodon	*lineolatus*	1	8	5	3	7	1	4	1	1
	Chaetodon	*lunula*	1	5	5	3	5	0	0	1	3
	Chaetodon	*lunulatus*	0	1	0	0	1	0	3	0	1
	Chaetodon	*melannotus*	0	0	0	0	0	0	2	2	0
	Chaetodon	*meyeri*	0	1	3	3	0	0	1	0	0
	Chaetodon	*ornatissimus*	0	1	4	2	0	0	2	2	0
	Chaetodon	*oxycephalus*	0	0	0	0	0	0	2	0	1
	Chaetodon	*selene*	1	5	0	0	2	1	0	0	0
	Chaetodon	*speculum*	0	1	1	1	0	0	1	0	0
	Chaetodon	*trifascialis*	0	4	3	4	0	0	6	0	0
	Chaetodon	*ulietensis*	0	2	0	2	0	0	1	0	2
	Chaetodon	*unimaculatus*	0	0	3	0	0	0	0	0	0
	Chaetodon	*vagabundus*	2	2	0	0	0	0	1	0	1
	Coradion	*altivelis*	0	2	0	0	0	0	0	0	0
	Coradion	*chrysozonus*	0	1	2	0	0	0	0	1	0

Order/family	Genus	species	WGB	ECH	BAW	BAE	HEY	SH25	EUG	VUL	GOE
	Forcipiger	*flavissimus*	0	5	1	4	3	0	5	1	0
	Hemitaurichthys	*polylepis*	0	0	1	0	0	0	1	2	0
	Heniochus	*acuminatus*	89	12	3	2	13	17	2	3	0
	Heniochus	*singularius*	0	8	3	5	5	0	2	0	3
	unk	*sp1*	0	0	0	0	0	0	1	0	0
Cirrhitidae		**Hawkfishes**									
	Cirrhitichthys	*oxycephalus*	0	0	0	0	3	0	2	0	0
	Paracirrhites	*forsteri*	0	0	0	0	1	0	1	1	0
Echeneidae		**Suckerfishes**									
	Echeneis	*naucrates*	7	9	16	20	19	10	18	10	4
Ephippidae		**Batfishes**									
	Platax	*batavianus*	0	0	0	0	3	0	0	0	1
	Platax	*orbicularis*	0	0	3	0	0	0	0	0	0
	Platax	*teira*	0	5	1	1	3	0	2	5	1
Gobiidae		**Gobies**									
	Pseudogobius	*olorum*	0	10	0	0	0	0	0	0	0
Haemulidae		**Painted Sweetlips**									
	Diagramma	*labiosum*	0	0	0	0	1	0	1	0	0
	Plectorhinchus	*picus*	0	0	1	0	1	0	0	0	0

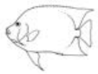
Order/family	Genus	species	WGB	ECH	BAW	BAE	HEY	SH25	EUG	VUL	GOE
	Plectorhinchus	*vittatus*	0	4	2	0	0	0	1	0	0
Kyphosidae		**Drummers**									
	Kyphosus	*vaigiensis*	0	0	0	0	0	0	0	0	1
Labridae		**Wrasses and Tuskfishes**									
	Anampses	*lennardi*	0	0	0	0	0	0	1	0	2
	Bodianus	*bilunulatus*	0	1	0	0	0	0	0	0	0
	Bodianus	*diana*	0	1	7	2	1	0	2	0	1
	Cheilinus	*fasciatus*	0	0	0	0	0	0	2	0	0
	Cheilinus	*trilobatus*	0	6	0	3	7	0	1	1	0
	Cheilinus	*undulatus*	0	0	1	0	0	0	0	0	0
	Choerodon	*jordani*	0	0	1	3	5	0	0	0	2
	Cirrhilabrus	*exquisitus*	0	38	0	37	1	0	2	0	0
	Cirrhilabrus	*randalli*	0	0	0	0	61	0	0	0	0
	Cirrhilabrus	*sp1*	317	152	24	196	448	185	563	154	313
	Cirrhilabrus	*sp2*	0	16	11	88	226	29	2	0	217
	Cirrhilabrus	*temminckii*	0	0	0	0	1	0	0	0	0
	Coris	*aygula*	0	0	2	0	1	0	0	0	1
	Coris	*caudimacula*	0	0	1	0	0	0	1	0	4
	Coris	*dorsomacula*	0	0	1	0	1	0	0	0	0
	Coris	*gaimard*	1	3	3	11	20	0	4	0	0
	Coris	*pictoides*	0	0	0	0	1	0	1	0	0
	Gomphosus	*varius*	0	0	0	0	0	0	3	0	0

Order/family	Genus	species	WGB	ECH	BAW	BAE	HEY	SH25	EUG	VUL	GOE
	Halichoeres	*all*	0	3	2	10	4	2	0	0	1
	Halichoeres	*chrysus*	0	1	2	4	3	0	4	0	0
	Halichoeres	*hartzfeldii*	0	6	1	27	38	10	0	1	0
	Halichoeres	*hortulanus*	0	3	4	3	7	0	2	1	3
	Halichoeres	*nebulosus*	0	4	0	3	5	0	1	1	0
	Halichoeres	*prosopeion*	0	0	0	0	0	0	0	0	1
	Halichoeres	*zeylonicus*	0	6	9	5	39	13	9	3	1
	Hemigymnus	*fasciatus*	0	2	0	0	0	0	0	0	0
	Hologymnosus	*annulatus*	0	1	1	0	0	0	0	0	0
	Hologymnosus	*doliatus*	5	10	6	13	1	0	3	3	1
	Iniistius	*pavo*	3	0	1	0	0	7	1	0	0
	Labroides	*bicolor*	0	3	1	0	1	0	0	0	0
	Labroides	*dimidiatus*	2	27	10	38	28	4	24	11	16
	Leptojulis	*cyanopleura*	0	0	0	0	0	1	0	0	0
	Novaculichthys	*taeniourus*	0	0	0	0	3	0	3	1	0
	Oxycheilinus	*digrammus*	4	7	1	8	7	0	5	1	1
	Oxycheilinus	*sp1*	8	0	0	0	23	0	2	0	3
	Oxycheilinus	*sp2*	2	0	0	0	0	0	0	0	0
	Oxycheilinus	*sp3*	0	1	0	0	3	0	0	0	0
	Oxycheilinus	*unifasciatus*	0	4	3	2	1	0	2	1	1
	Pseudodax	*moluccanus*	0	1	6	4	1	0	2	0	2
	Pseudojuloides	*severnsi*	15	2	0	2	21	12	41	10	3
	Pseudolabrus	*sp1*	0	0	0	0	0	0	1	0	0
	Pteragogus	*sp1*	0	1	0	0	0	0	0	0	0

Order/family	Genus	species	WGB	ECH	BAW	BAE	HEY	SH25	EUG	VUL	GOE
	Stethojulis	*sp1*	0	0	0	0	0	0	4	0	0
	Thalassoma	*amblycephalum*	0	0	2	7	0	0	1	0	0
	Thalassoma	*jansenii*	0	3	1	5	5	0	4	0	1
	Thalassoma	*lunare*	0	17	1	14	15	0	18	4	0
	unk	*all*	3	2	2	0	11	37	6	2	53
Lethrinidae		**Emperors**									
	Gymnocranius	*grandoculis*	24	1	10	18	18	14	5	12	25
	Lethrinus	*amboinensis*	102	6	46	87	65	140	45	21	81
	Lethrinus	*atkinsoni*	9	219	50	30	181	84	96	288	134
	Lethrinus	*erythracanthus*	0	3	3	3	4	0	2	0	0
	Lethrinus	*microdon*	0	11	0	0	5	1	7	0	1
	Lethrinus	*nebulosus*	0	6	0	1	24	85	5	3	5
	Lethrinus	*olivaceus*	4	29	25	42	47	9	56	22	16
	Lethrinus	*ravus*	10	0	55	58	1	80	0	0	1
	Lethrinus	*rubrioperculatus*	162	142	96	159	365	318	134	87	220
	Lethrinus	*semicinctus*	0	1	3	0	6	1	0	0	0
	Lethrinus	*sp1*	0	0	0	0	56	5	6	0	6
	Lethrinus	*sp2*	0	40	0	0	0	0	0	0	0
	Lethrinus	*xanthochilus*	0	0	0	0	0	0	0	0	1
	Monotaxis	*grandoculis*	0	3	10	2	7	0	6	3	1
	Aphareus	*furca*	0	0	0	2	0	0	0	0	0
	Aprion	*virescens*	8	6	5	16	17	6	6	4	5

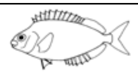
Order/family	Genus	species	WGB	ECH	BAW	BAE	HEY	SH25	EUG	VUL	GOE
Lutjanidae		**Snappers/sea perches**									
	Lutjanus	*bohar*	2	117	60	123	110	23	95	66	45
	Lutjanus	*decussatus*	0	0	0	0	2	0	0	0	0
	Lutjanus	*erythropterus*	0	0	0	0	7	0	0	0	0
	Lutjanus	*fulviflamma*	0	6	0	0	0	0	14	2	1
	Lutjanus	*gibbus*	4	16	8	6	7	11	4	2	6
	Lutjanus	*kasmira*	0	0	3	0	0	0	0	0	2
	Lutjanus	*lemniscatus*	0	3	0	0	1	2	0	0	0
	Lutjanus	*rivulatus*	0	16	4	7	22	5	6	4	0
	Lutjanus	*sebae*	0	0	0	0	13	2	3	0	0
	Lutjanus	*sp1*	0	1	0	0	0	0	0	0	0
	Macolor	*macularis*	0	16	13	3	22	5	12	6	7
	Macolor	*niger*	0	12	6	19	2	0	4	1	6
	Pinjalo	*lewisi*	0	0	0	0	0	9	0	0	0
	Symphorichthys	*spilurus*	2	1	0	0	1	0	0	0	0
	Symphorus	*nematophorus*	0	1	0	0	18	7	0	0	1
Malacanthidae		**Tilefishes**									
	Hoplolatilus	*cuniculus*	3	0	5	0	0	0	0	4	1
	Hoplolatilus	*sp1*	0	0	0	0	0	0	0	0	2
	Malacanthus	*brevirostris*	4	7	3	4	8	0	1	0	4
	Malacanthus	*latovittatus*	1	6	0	12	3	0	7	0	1

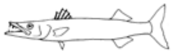
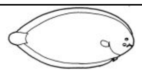
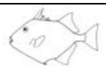
Order/family	Genus	species	WGB	ECH	BAW	BAE	HEY	SH25	EUG	VUL	GOE
Microdesmidae		**Wormfishes**									
	Ptereleotris	*evides*	0	0	0	0	0	0	0	1	0
	Ptereleotris	*heteroptera*	0	0	0	0	1	0	1	0	0
	Ptereleotris	*sp1*	0	0	0	1	1	55	1	0	1
	unk	*all*	0	0	1	0	0	3	0	0	0
Mullidae		**Goatfishes**									
	Mulloidichthys	*vanicolensis*	0	0	0	0	1	0	0	0	0
	Parupeneus	*barberinoides*	0	0	0	0	4	1	0	1	1
	Parupeneus	*barberinus*	2	0	2	1	8	1	1	1	1
	Parupeneus	*crassilabris*	0	0	0	0	1	0	0	0	0
	Parupeneus	*cyclostomus*	18	5	15	16	14	0	11	3	6
	Parupeneus	*indicus*	0	0	0	0	4	0	0	0	0
	Parupeneus	*multifasciatus*	2	17	17	40	70	1	8	19	4
	Parupeneus	*pleurostigma*	0	2	5	3	9	0	5	5	1
Nemipteridae		**Threadfin breams**									
	Pentapodus	*aureofasciatus*	3	0	0	1	33	0	0	0	0
	Pentapodus	*nagasakiensis*	1	0	0	0	3	0	0	0	0
	Scolopsis	*xenochrous*	18	30	4	44	70	1	7	24	16
Pinguipedidae		**Grubfishes**									
	Parapercis	*clathrata*	0	0	0	0	0	0	0	1	0
	Parapercis	*sp1*	4	16	4	9	20	0	4	8	3

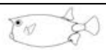
Order/family	Genus	species	WGB	ECH	BAW	BAE	HEY	SH25	EUG	VUL	GOE
	Parapercis	*xanthozona*	2	0	1	4	0	0	1	3	0
Pomacanthidae		**Angelfishes**									
	Apolemichthys	*trimaculatus*	12	35	10	15	28	1	39	9	10
	Centropyge	*bicolor*	4	23	1	14	25	0	18	2	6
	Centropyge	*tibicen*	0	3	3	2	9	0	5	2	2
	Centropyge	*vroliki*	0	6	2	6	8	0	4	1	4
	Genicanthus	*lamarck*	0	6	4	0	45	0	4	0	4
	Pomacanthus	*imperator*	6	17	14	24	26	2	19	16	8
	Pomacanthus	*semicirculatus*	0	0	0	0	0	0	0	0	1
	Pomacanthus	*sexstriatus*	0	0	0	0	9	0	0	0	0
	Pygoplites	*diacanthus*	0	0	1	0	1	0	6	1	0
Pomacentridae		**Damselfishes**									
	Acanthochromis	*sp1*	0	0	2	0	0	0	0	0	0
	Amblypomacentrus	*breviceps*	0	0	0	0	0	0	1	0	0
	Amphiprion	*clarkii*	0	0	0	0	0	0	1	0	0
	Amphiprion	*percula*	0	0	0	3	0	0	0	0	0
	Amphiprion	*sp1*	0	0	0	0	1	0	1	0	0
	Chromis	*amboinensis*	0	0	0	0	10	0	0	0	0
	Chromis	*fumea*	0	1	1	11	4	0	1	0	0
	Chromis	*margaritifer*	0	37	11	3	6	0	47	4	8
	Chromis	*sp1*	0	12	100	0	0	0	1	0	0
	Chromis	*sp2*	0	0	0	0	0	0	70	0	0

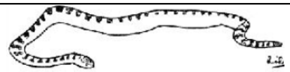
Order/family	Genus	species	WGB	ECH	BAW	BAE	HEY	SH25	EUG	VUL	GOE
	Chromis	*weberi*	0	62	125	48	60	0	4	21	80
	Chromis	*westaustralis*	0	0	0	0	0	0	105	0	0
	Chrysiptera	*caeruleolineata*	0	0	0	6	0	0	0	0	0
	Chrysiptera	*sp1*	0	0	0	0	0	0	1	0	0
	Dascyllus	*reticulatus*	0	41	13	37	1	0	139	5	1
	Dascyllus	*trimaculatus*	0	12	3	4	11	1	3	1	0
	Plectroglyphidodon	*dickii*	0	0	0	3	0	0	0	0	0
	Plectroglyphidodon	*johnstonianus*	0	0	1	0	0	0	1	0	0
	Pomacantrus	*sp1*	0	1	0	1	0	0	0	0	2
	Pomacentrus	*coelestis*	9	523	20	171	392	34	199	193	27
	Pomacentrus	*milleri*	0	0	0	0	0	0	1	0	0
	Pomacentrus	*moluccensis*	0	1	0	0	0	0	0	0	0
	Pomacentrus	*vaiuli*	0	3	0	0	0	0	1	0	0
	Pomachromis	*richardsoni*	0	0	0	20	0	0	0	0	0
	unk	*all*	5	1	0	2	43	0	3	116	151
Pseudochromidae		**Dottybacks**									
	Labracinus	*lineatus*	0	0	0	0	0	0	1	0	1
Rachycentridae		**Cobia**									
	Rachycentron	*canadum*	0	0	0	0	1	0	0	2	0
Scaridae		**Parrotfishes**									
	Cetoscarus	*bicolor*	0	0	1	0	0	0	0	0	0

Order/family	Genus	species	WGB	ECH	BAW	BAE	HEY	SH25	EUG	VUL	GOE
	Chlorurus	*bleekeri*	0	28	0	8	25	1	2	2	17
	Chlorurus	*microrhinos*	0	0	0	1	0	0	2	0	0
	Chlorurus	*sordidus*	0	8	3	9	10	0	16	4	4
	Hipposcarus	*longiceps*	0	9	2	0	4	0	0	0	1
	Scarus	*chameleon*	0	0	0	0	1	0	0	0	0
	Scarus	*dimidiatus*	0	1	0	0	0	0	0	0	0
	Scarus	*forsteni*	0	1	5	2	10	0	6	0	2
	Scarus	*ghobban*	1	4	1	2	10	0	1	1	0
	Scarus	*oviceps*	1	10	4	5	9	0	5	5	2
	Scarus	*psittacus*	0	0	0	0	2	0	0	0	0
	Scarus	*rivulatus*	0	1	0	1	2	0	0	0	1
	Scarus	*rubroviolaceus*	2	1	0	3	37	0	10	9	0
	Scarus	*schlegeli*	0	16	1	2	9	1	4	0	2
	Scarus	*sp1*	0	0	10	0	0	0	2	9	0
	Scarus	*sp3*	0	0	1	0	0	0	0	0	0
	unk	*all*	0	2	0	2	3	2	1	0	0
Scombridae		**Tuna and mackerel**									
	Grammatorcynus	*bilineatus*	0	0	0	0	0	0	8	0	0
	Gymnosarda	*unicolor*	4	5	2	4	7	1	6	6	12
	Scomberomorus	*commerson*	1	2	0	3	5	3	1	1	3
	Scomberomorus	*queenslandicus*	0	0	0	0	0	0	1	0	0
Serranidae		**Cods and groupers**									

Order/family	Genus	species	WGB	ECH	BAW	BAE	HEY	SH25	EUG	VUL	GOE
	Aethaloperca	*rogaa*	0	8	10	14	16	0	14	2	5
	Cephalopholis	*boenak*	0	1	0	1	0	0	2	0	0
	Cephalopholis	*miniata*	0	3	8	0	1	0	3	1	0
	Cephalopholis	*sonnerati*	0	0	1	1	1	0	0	2	0
	Cephalopholis	*sp1*	0	0	0	0	0	0	2	0	0
	Cephalopholis	*sp2*	0	1	0	0	0	0	0	0	0
	Cephalopholis	*spiloparaea*	0	0	0	0	1	0	0	0	0
	Cephalopholis	*urodeta*	0	3	10	15	3	0	4	4	4
	Epinephelus	*bilobatus*	0	4	0	0	5	0	0	0	0
	Epinephelus	*fasciatus*	0	1	1	2	3	0	2	2	0
	Epinephelus	*fuscoguttatus*	0	1	0	0	3	0	0	0	0
	Epinephelus	*maculatus*	1	0	0	0	0	0	0	0	0
	Epinephelus	*malabaricus*	0	1	0	0	5	0	0	0	0
	Epinephelus	*rivulatus*	0	0	1	0	0	0	0	0	0
	Epinephelus	*sp1*	0	0	1	0	0	0	0	0	0
	Plectropomus	*laevis*	0	0	0	1	0	0	1	0	0
	Plectropomus	*leopardus*	0	4	0	0	1	0	2	5	2
	Plectropomus	*maculatus*	0	1	0	0	0	0	1	0	0
	Pseudanthias	*sp1*	0	0	0	0	1	0	0	0	0
	Variola	*albimarginata*	7	28	9	30	30	9	14	8	4
	Variola	*louti*	1	4	5	8	4	0	7	6	6
Siganidae		**Rabbitfishes**									
	Siganus	*argenteus*	109	0	30	27	22	19	70	35	17

Order/family	Genus	species	WGB	ECH	BAW	BAE	HEY	SH25	EUG	VUL	GOE
	Siganus	*fuscescens*	0	0	0	2	3	0	0	0	1
	Siganus	*punctatissimus*	0	0	1	0	0	0	0	0	0
	Siganus	*punctatus*	0	0	2	3	3	3	1	1	1
	unk	*sp1*	0	0	0	0	0	0	1	0	0
Sphyraenidae		**Barracuda**									
	Sphyraena	*barracuda*	0	0	0	1	5	0	1	1	0
	Sphyraena	*qenie*	0	0	0	0	0	0	1	0	0
Zanclidae		**Moorish Idols**									
	Zanclus	*cornutus*	14	18	11	14	15	2	21	8	17
Bothidae		**Flounders**									
	unk	*sp1*	0	0	0	0	1	0	0	0	0
Soleidae		**Soles**									
	Heteromycteris	*hartzfeldi*	0	0	0	3	3	2	0	0	0
Tetraodontiformes											
Balistidae		**Triggerfishes**									
	Abalistes	*stellatus*	0	3	0	0	38	17	11	0	0
	Balistapus	*undulatus*	0	9	4	5	12	0	10	5	3
	Balistoides	*conspicillum*	1	8	7	7	9	1	5	3	2
	Balistoides	*viridescens*	1	17	7	17	13	3	3	5	5

Order/family	Genus	species	WGB	ECH	BAW	BAE	HEY	SH25	EUG	VUL	GOE
	Canthidermis	*maculatus*	0	0	17	1	0	0	2	1	8
	Melichthys	*niger*	1	0	0	0	0	0	5	0	0
	Melichthys	*vidua*	3	0	0	0	0	0	14	0	1
	Odonus	*niger*	7	8	129	376	90	27	112	64	30
	Pseudobalistes	*flavimarginatus*	0	12	0	2	9	0	2	2	2
	Pseudobalistes	*fuscus*	1	0	2	43	4	2	16	5	13
	Rhinecanthus	*rectangulus*	0	0	0	0	0	0	0	1	0
	Sufflamen	*bursa*	0	4	1	2	0	0	0	1	0
	Sufflamen	*chrysopterum*	1	17	5	11	24	0	12	10	0
	Sufflamen	*fraenatum*	2	11	6	19	30	8	6	3	6
	unk	*all*	0	0	0	1	0	0	0	1	0
Diodontidae		**Spiky globefishes**									
	Diodon	*hystrix*	0	0	0	0	1	0	0	1	0
Monacanthidae		**Leatherjackets/filefish**									
	Aluterus	*monoceros*	0	0	0	0	0	0	0	0	1
	Aluterus	*scriptus*	3	6	5	3	4	2	3	8	7
	Cantherhines	*dumerilii*	0	2	2	5	3	0	3	1	1
	Cantherhines	*pardalis*	0	1	0	0	3	0	0	0	0
Ostraciidae		**Boxfishes**									
	Lactoria	*cornuta*	0	0	0	0	0	0	0	1	0
	Ostracion	*cubicus*	0	1	0	0	0	1	0	1	0

Order/family	Genus	species	WGB	ECH	BAW	BAE	HEY	SH25	EUG	VUL	GOE
Tetraodontidae		**Pufferfishes**									
	Arothron	*hispidus*	4	0	1	1	0	0	0	2	0
	Arothron	*meleagris*	0	0	0	1	0	0	0	0	0
	Arothron	*sp*	0	0	0	0	0	0	1	0	0
	Arothron	*sp1*	0	0	0	1	1	0	0	0	0
	Arothron	*stellatus*	0	0	1	0	0	1	1	0	0
	Lagocephalus	*sceleratus*	0	0	0	0	7	0	0	0	0
Reptilia: ***Squamata***											
Hydrophiidae		**Seasnakes**									
	Aipysurus	*laevis*	1	10	11	11	14	0	1	12	6
	Hydrophis	*ornatus*	0	0	0	0	1	0	0	3	0
	unk	*all*	4	6	4	9	13	1	1	7	2

Appendix 4.2 Modelled responses to environmental correlates for fish abundance and diversity

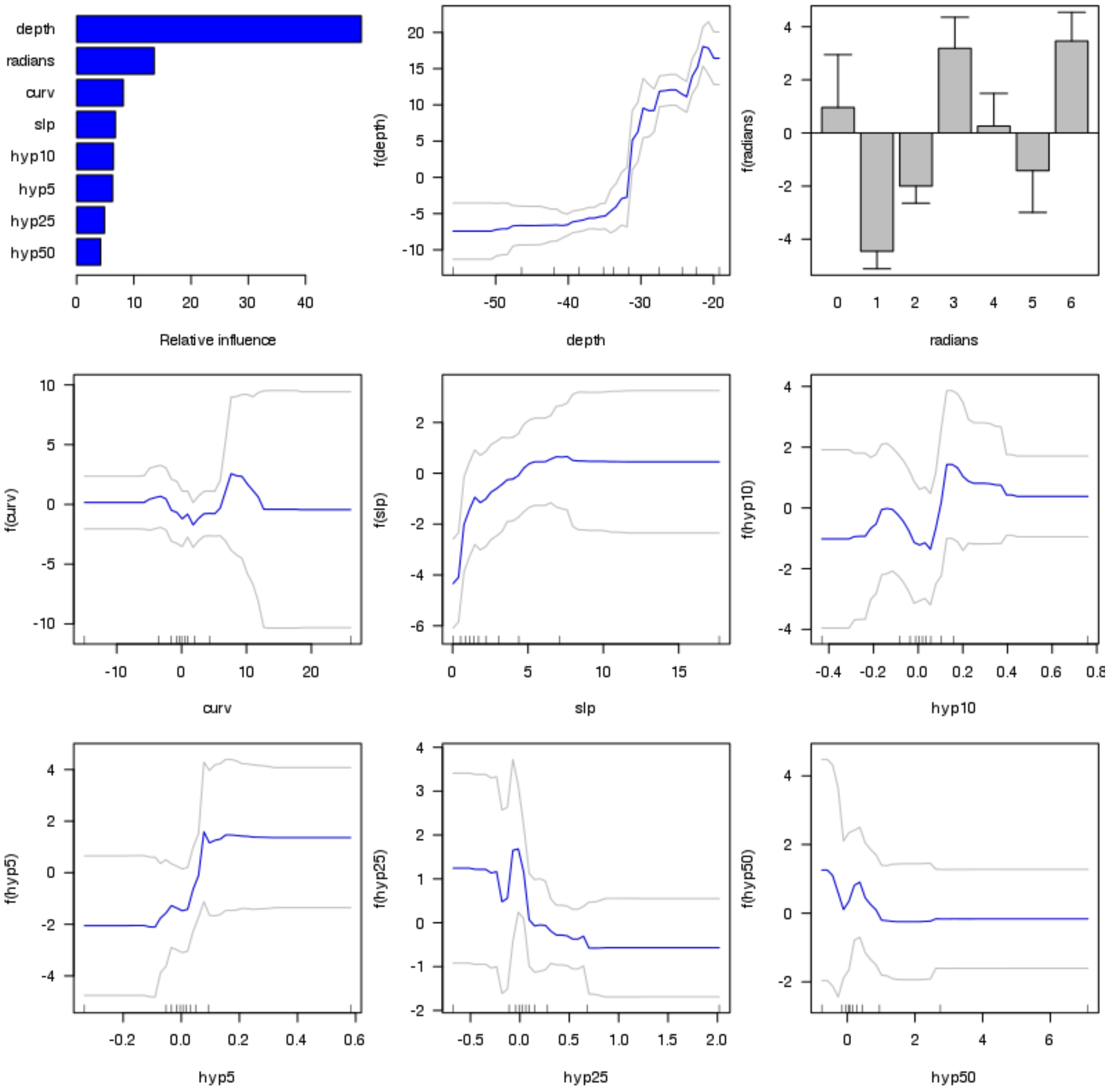


Figure A4.2.1. BRUVS fish species richness (total number of species n) Y-axes are mean centered total number of species (note models only containing multibeam derived variables, as in Chapter 3 habitat models, and depth is included as a negative value).

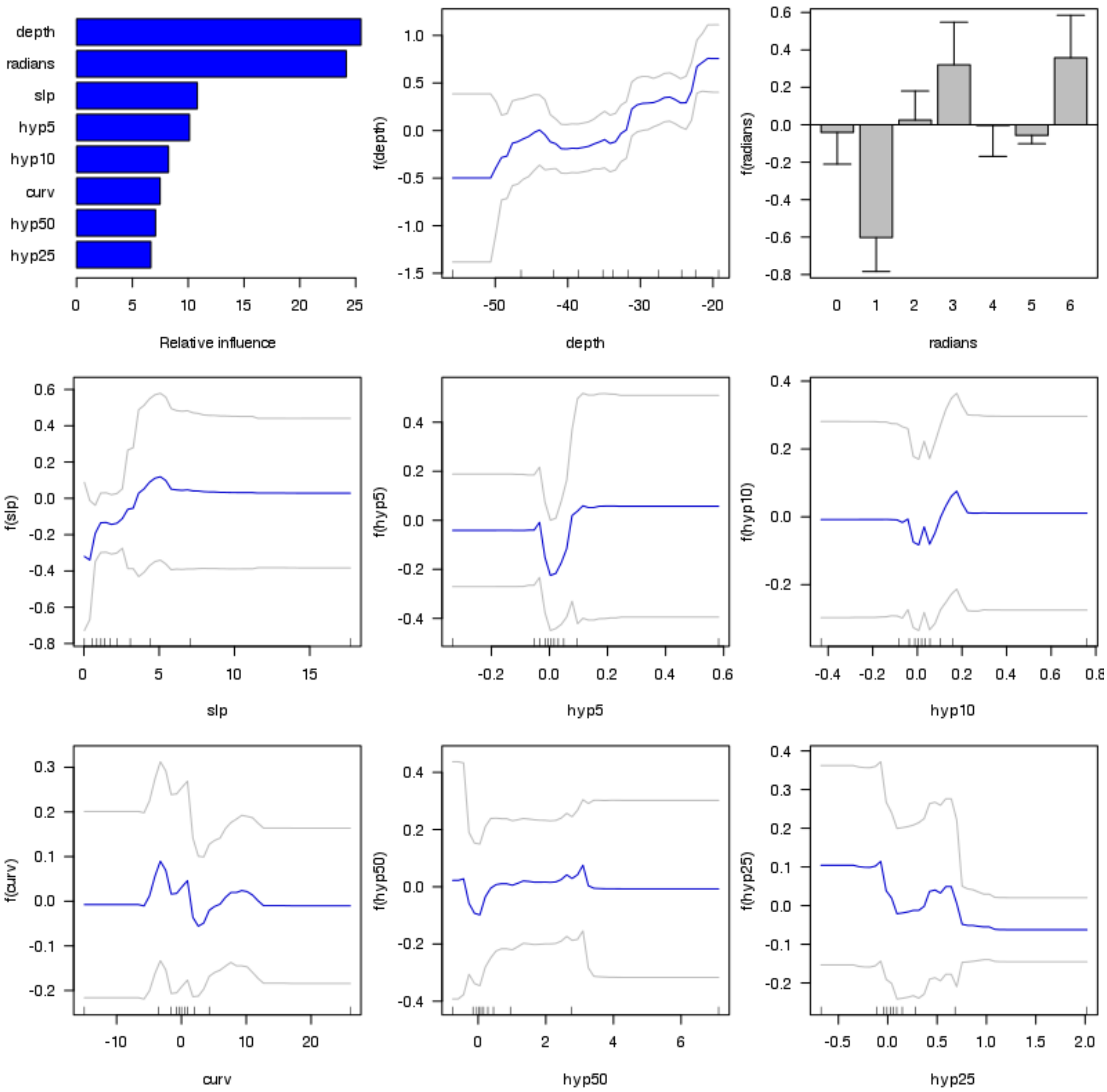


Figure A4.2.2. BRUVS fish species raw abundance (total n) partial response plots. Y-axes are mean centered abundance. (note models only containg multibeam derived variables, as in Chapter 3 habitat models, and depth is included as a negative value).

Appendix 4.3 ABT Analysis Partial Dependency Plots.

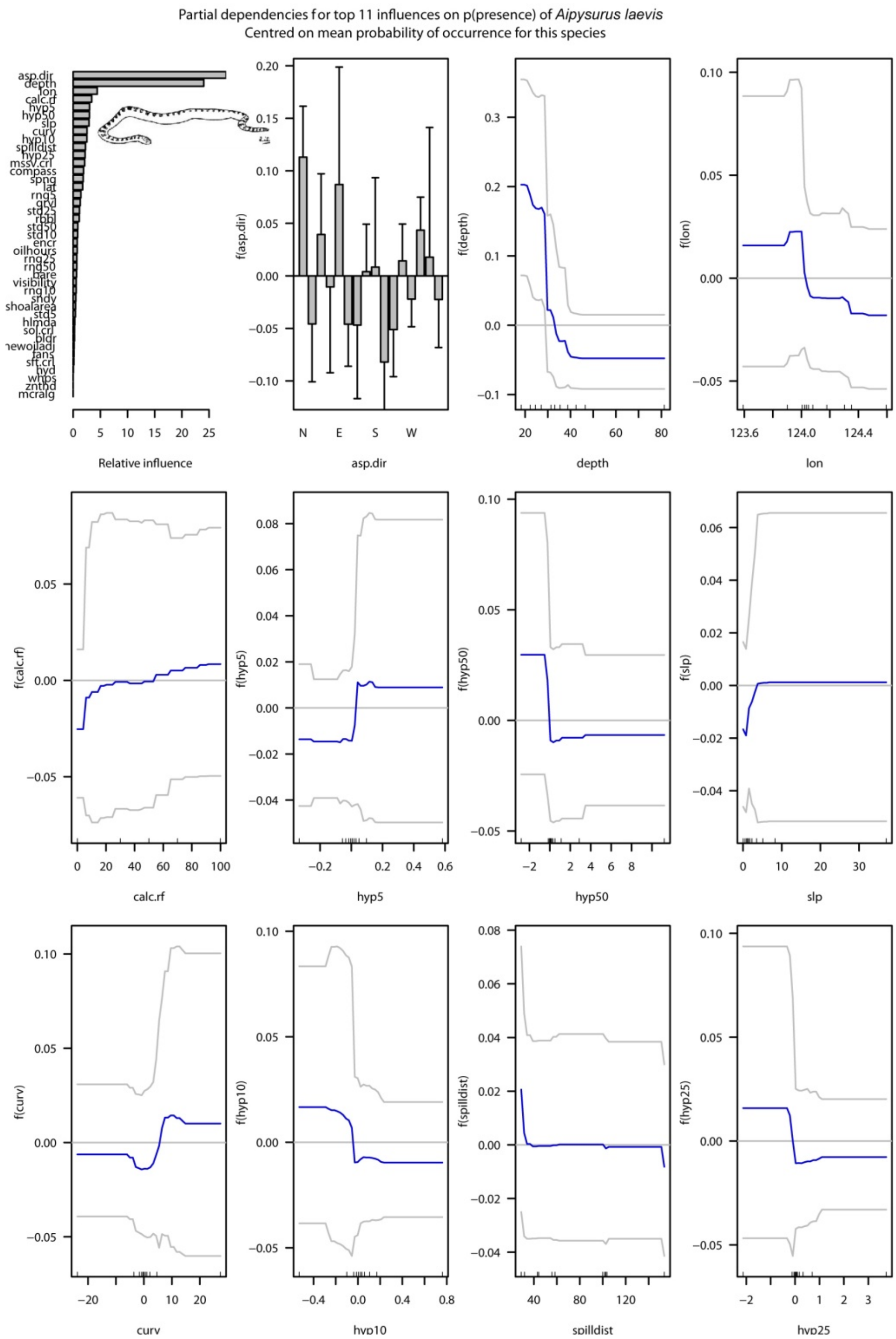


Figure A4.3.1. Partial dependency plots (probability scale) of the 11 major influences on the probability of occurrence of the olive sea snake *Aipysurus laevis*. The full model of 41 covariates was applied, allowing for 3 way interactions amongst variables. Horizontal dotted lines (red) show the response is centred on the average probability of occurrence across all drops. Dotted lines (grey) around the response line are 2 standard errors. BRUVS in depths shallower than 30m had higher probability than average of encountering sea snakes, but the influence of “spilldist” was not noticeably positive.

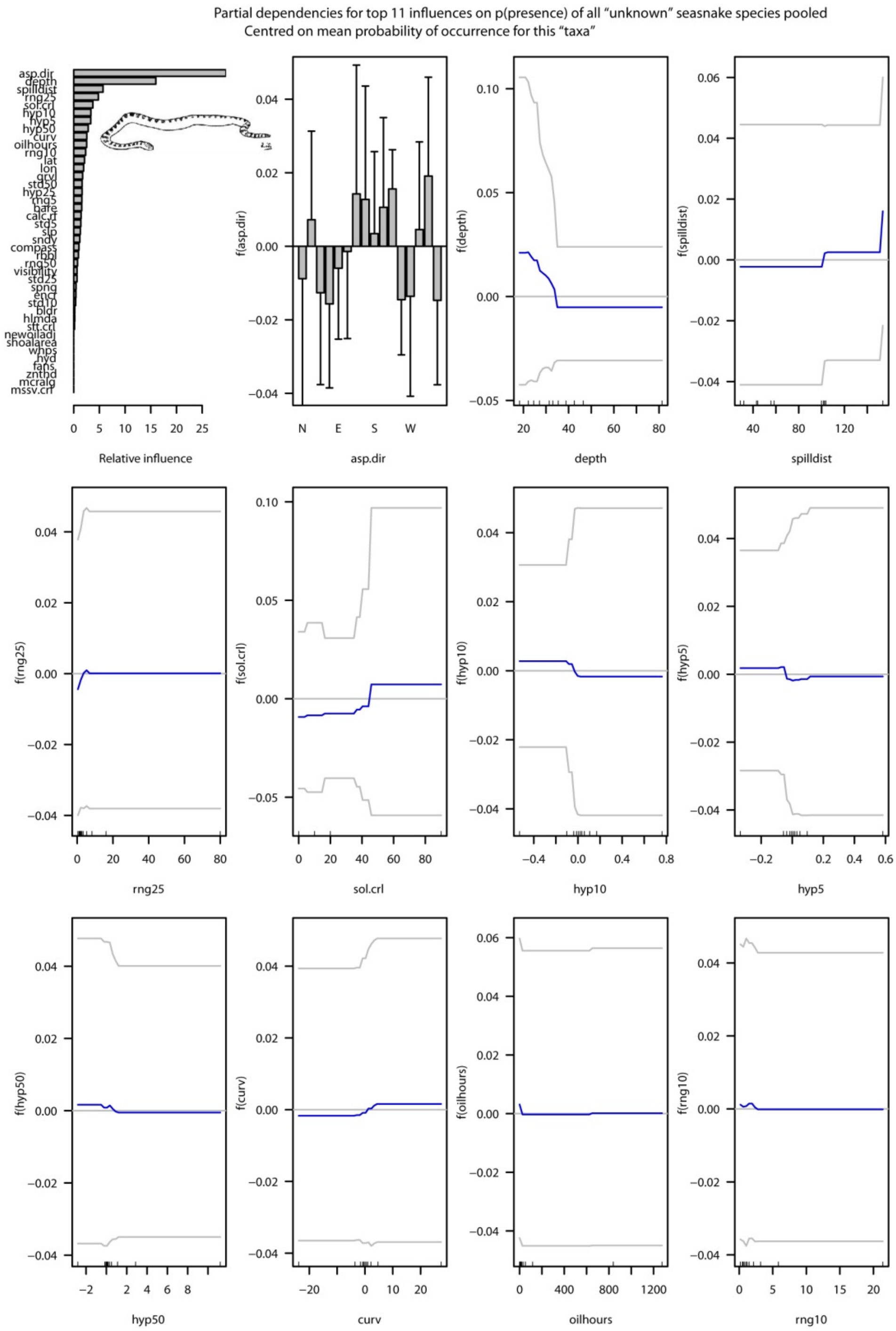


Figure A4.3.2. Partial dependency plots (probability scale) of the 11 major influences on the probability of occurrence of the unidentified sea snakes pooled into one "taxa". All conventions follow Figure A4.3.1. BRUVS at sites sloping toward the north had lower than average probability of encountering these sea snakes, and the converse was true for southward sloping sites. The influence of "spilldist" was about 2% across the range of values.

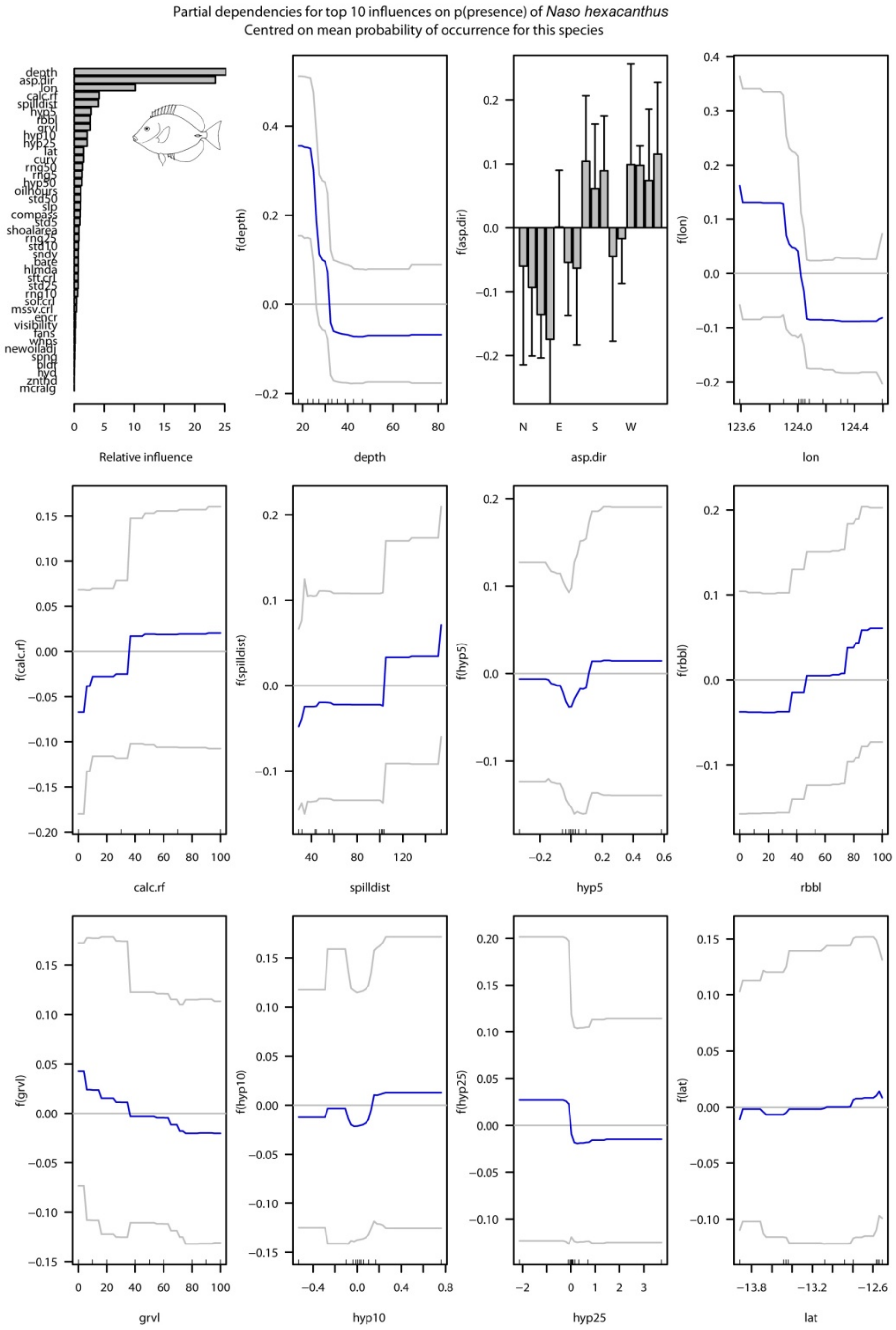


Figure A4.3.3. Partial dependency plots (probability scale) of the 11 major influences on the probability of occurrence of the large facultative planktivore *Naso hexacanthus*. All conventions follow Figure A4.3.1. BRUVS at sites sloping toward the north and east had lower than average probability of encountering this species, and the converse was true for southward and westward sloping sites. The positive influence of "spilldist" was about 10% across the range of distances from the Montara well head platform, but this was parallel with an influence of about 30% increase in probability across the (cross-shelf) decrease in longitude.

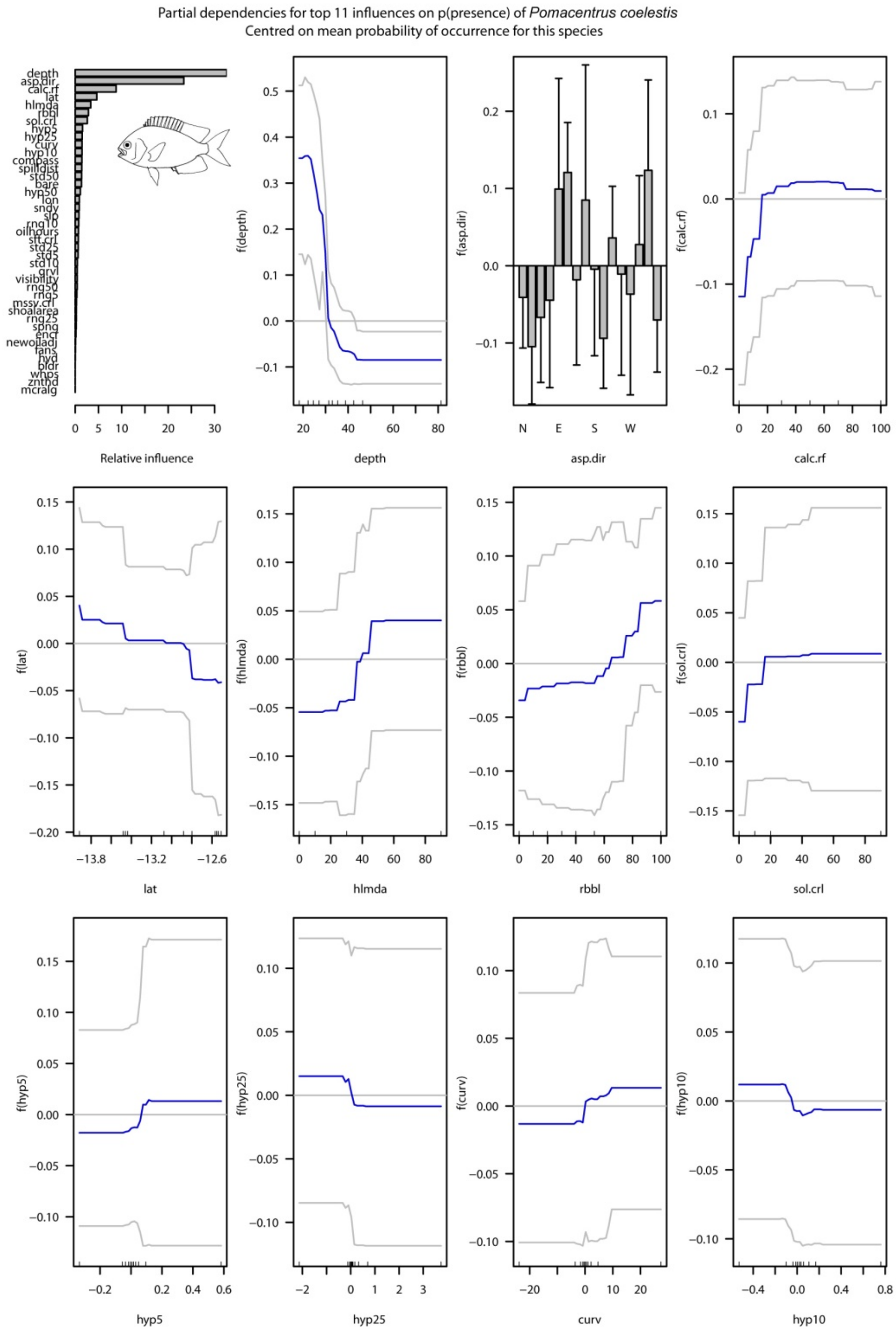


Figure A4.3.4. Partial dependency plots (probability scale) of the 11 major influences on the probability of occurrence of the small, schooling planktivore *Pomacentrus coelestis*. Shallow depths were major influences on probability of encountering this species, with about a 10% decline in habitats where the cover of reefal substrata was less than 20%. All conventions follow Figure A4.3.1.

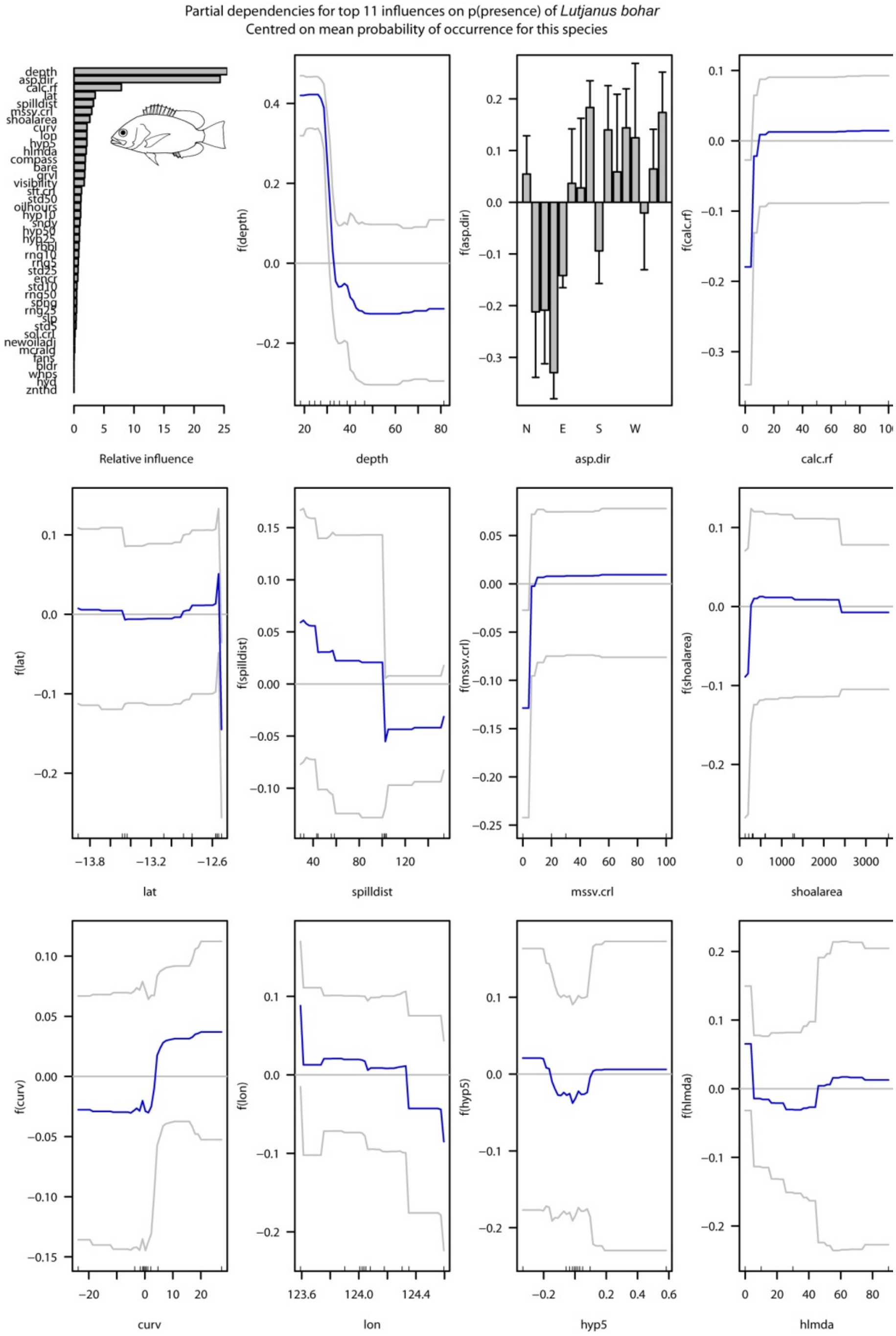


Figure A4.3.5. Partial dependency plots (probability scale) of the 11 major influences on the probability of occurrence of the large, piscivore *Lutjanus bohar*. Shallow depths below 30m were major influences on probability of encountering this species, with about a 10% decline in habitats where the cover of reefal substrata was less than 20%. These patterns closely matched those of the small planktivore *Pomacentrus coelestis*, which is probably an important prey item. All conventions follow Figure A4.3.1.

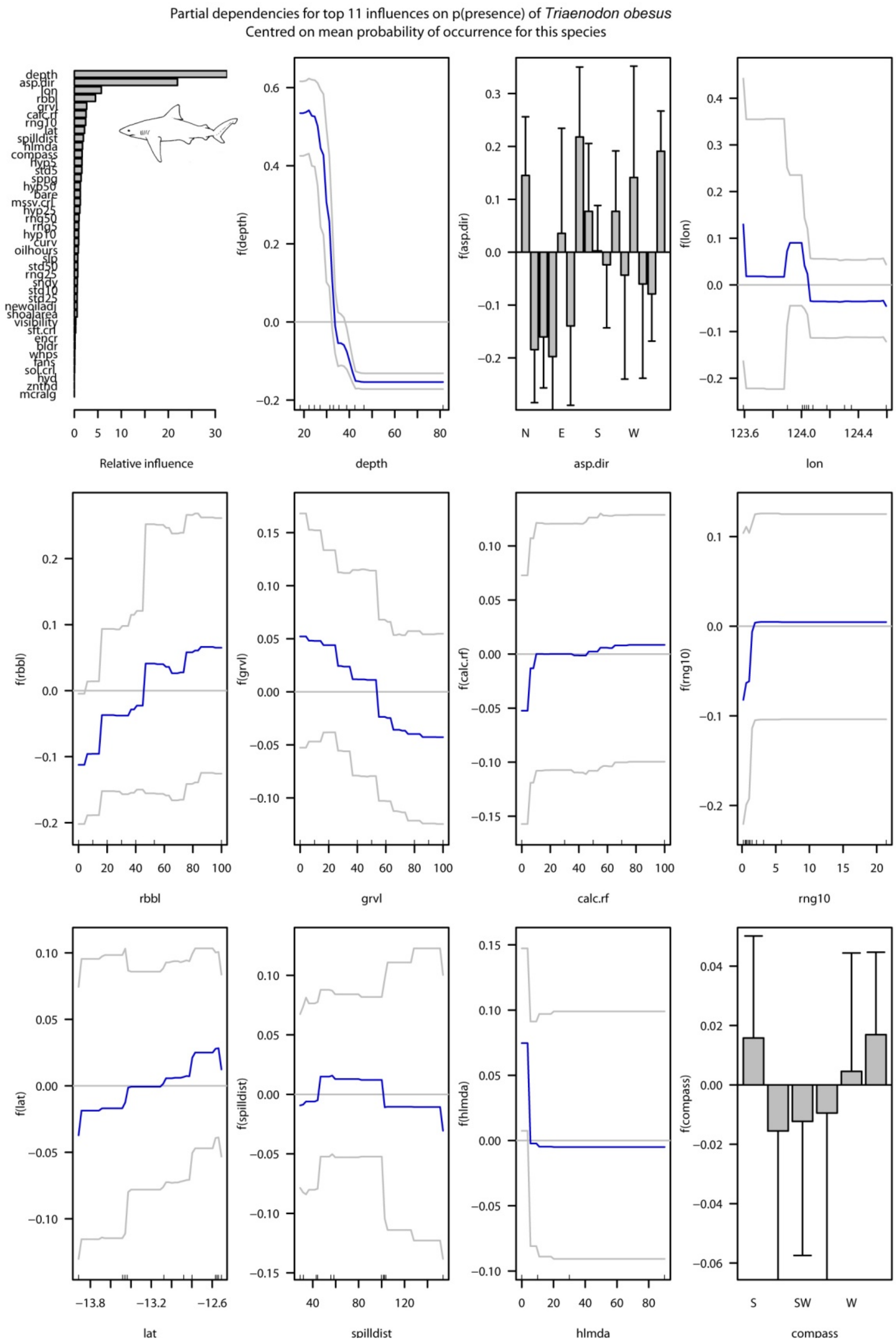


Figure A4.3.6. Partial dependency plots (probability scale) of the 11 major influences on the probability of occurrence of the white-tip reef shark *Triaenodon obesus*. Shallow depths below 30m and aspect direction were major influences on probability of encountering this species, with an important influence of rubbly seabeds. All conventions follow Figure A4.3.1.

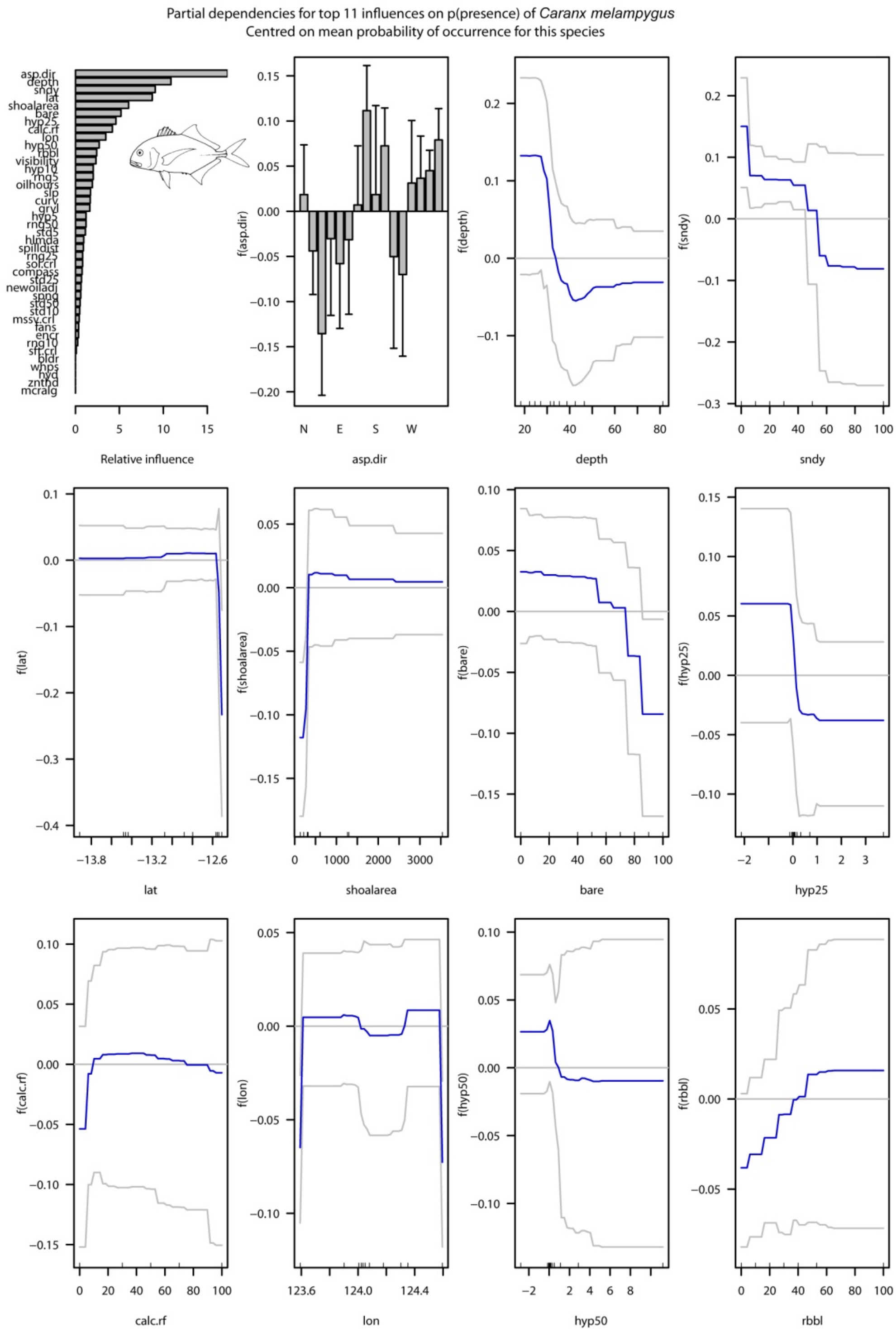


Figure A4.3.7. Partial dependency plots (probability scale) of the 11 major influences on the probability of occurrence of the fast piscivore *Caranx melamypgus*. Shallow depths below 30 m and aspect direction were major influences on probability of encountering this species, with a higher probability of occurrence on seafloors with very low coverage of sand. As for the previous species, BRUVS sites sloping toward the quadrants between north and east had lower than average probability of occurrence of *Caranx melampygus*. All conventions follow Figure A4.3.1.

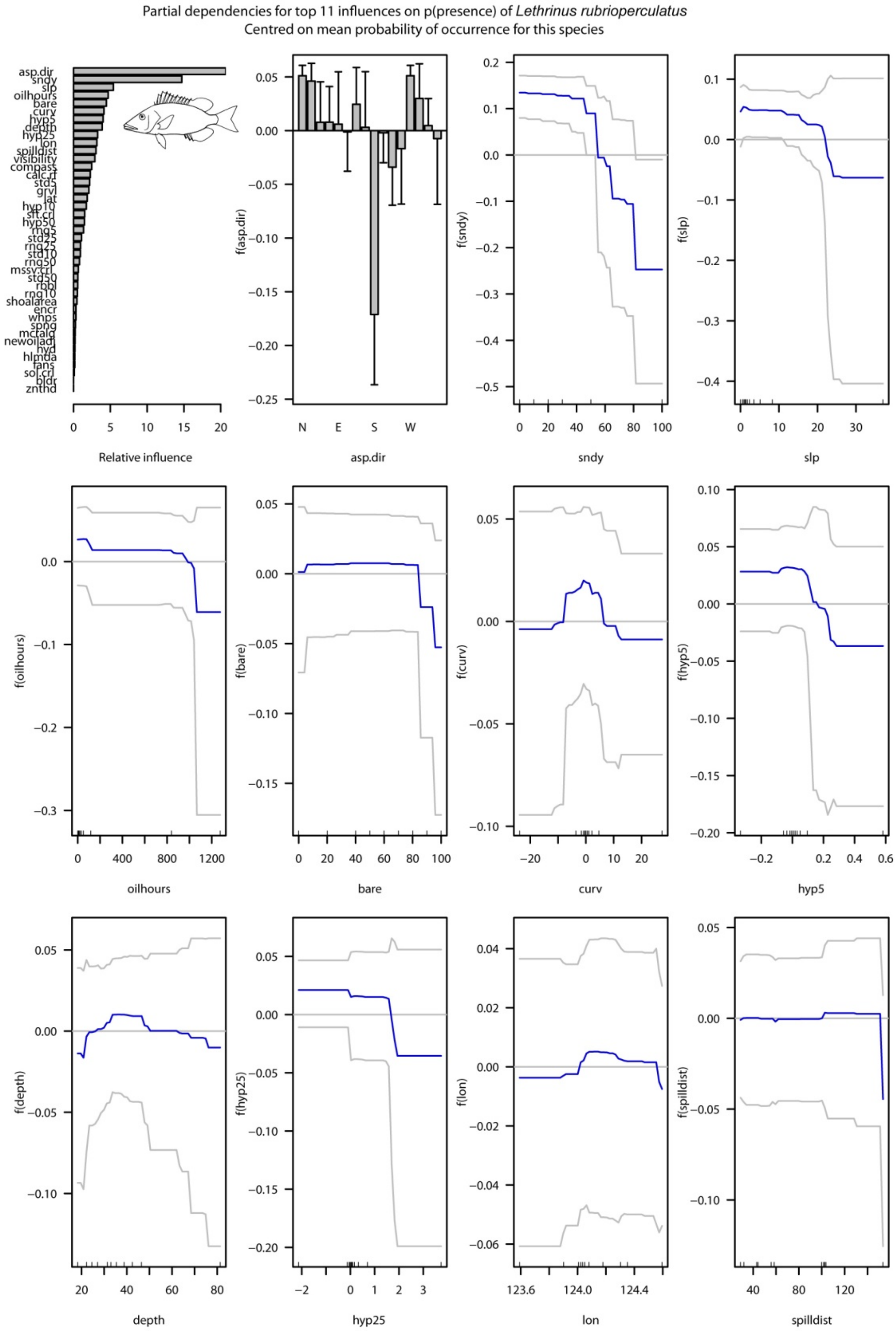


Figure A4.3.8. Partial dependency plots (probability scale) of the 11 major influences on the probability of occurrence of the demersal carnivore *Lethrinus rubrioperculatus*. This species was the most prevalent in the entire dataset, occurring at 208 (84%) of the 248 BRUVS sites. Unlike the species in the previous plots, BRUVS sites sloping toward the quadrants between north and east had a *higher* than average probability of occurrence of *Lethrinus rubrioperculatus*. There were higher than average probabilities of occurrence at flatter sites where coverage of sand on the seafloor was less than 50% and slopes were less than 10 degrees. All conventions follow Figure A4.3.1.

Appendix 4.4 ABT analysis covariates :

Table A4.4.1. The influence of the top 39 of the 41 explanatory covariates used in aggregated boosted regression trees (abt) to predict the occurrence (presence/absence) of the 54 most prevalent species shown in Table 4.7. Species are ranked in terms of their *rel.pred.err* from Table 4.7, so that the most predictable (lowest error) species are at the top. The explanatory covariates are ranked from left to right in decreasing order of their average influence across all 54 species. In these terms of average influence, from left to right, the direction of the slope at BRUVS sites (asp.dir), depth, and the %cover of reefal substrata were the primary predictors, with a steep drop to the influence of latitude, longitude and distance to the Montara well head platform (spilldist).

Species	**Predictor variables ranked from left to right in decreasing, average influence**																																						
	asp.dir	depth	calc.rf	lat	lon	spilldist	compass	mssv.crl	grvl	hyp5	curv	bare	slp	rbbl	hyp50	hyp25	hyp10	sndy	oilhours	std50	sft.crl	rng50	sol.crl	rng5	rng25	std5	std25	shoalarea	rng10	visibility	encr	std10	spng	hlmda	bldr	mcralg	fans	newoiladj	whps	hyd
Abalistes stellatus	12.1	12.1	4.7	32.2	6.3	0.8	2.7	0.1	0.8	0.5	0.5	0.6	0.6	0.6	0.7	0.4	0.4	7.6	0.2	2.4	0.2	0.5	0.1	0.4	0.1	0.4	0.1	6.6	0.3	0.2	2.7	0.3	0.2	0.7	0.0	0.1	0.0	0.0	0.0	0.8
Lethrinus nebulosus	18.7	2.7	0.5	25.8	11.5	3.2	1.8	0.1	1.2	1.0	2.4	0.6	1.5	1.6	0.5	1.1	0.9	0.5	1.9	1.6	1.9	0.3	0.1	4.1	0.4	0.6	0.2	1.4	1.3	1.3	5.9	0.5	0.1	0.5	0.0	0.9	0.0	0.5	0.0	1.0
Sufflamen chrysopterum	14.9	41.1	6.7	2.0	3.1	0.8	1.5	0.4	0.3	1.4	0.9	0.7	2.0	2.4	2.4	0.5	0.9	0.3	0.5	3.1	1.2	1.9	3.8	0.5	0.5	0.9	2.2	0.5	0.5	0.4	0.1	0.7	0.5	0.0	0.0	0.0	0.4	0.0	0.0	0.0
Chaetodon kleinii	22.9	13.3	25.5	2.6	3.1	1.0	3.2	6.4	0.4	0.9	1.4	1.3	1.5	0.3	1.5	0.7	1.0	0.2	0.8	2.4	0.5	2.1	0.5	0.3	1.4	0.8	0.5	0.3	0.4	0.8	0.6	0.8	0.2	0.0	0.0	0.0	0.0	0.0	0.3	0.0
Aluterus scriptus	25.6	1.9	0.2	3.3	5.0	6.6	2.3	0.5	0.5	2.3	5.3	0.7	4.0	0.6	3.8	4.4	4.6	0.3	0.9	3.5	0.5	2.9	0.2	2.1	2.6	1.3	3.2	0.3	1.5	0.4	0.2	1.5	5.0	0.3	0.0	0.0	0.5	0.5	0.0	0.2
Lutjanus bohar	24.4	25.5	7.9	3.5	2.1	3.2	1.9	3.0	1.8	2.1	2.2	1.9	0.4	0.8	0.9	0.9	1.1	1.0	1.1	1.2	1.3	0.4	0.2	0.7	0.4	0.3	0.7	2.6	0.8	1.7	0.6	0.5	0.4	2.0	0.0	0.1	0.0	0.1	0.0	0.0
Aethaloperca rogaa	18.2	10.6	12.1	1.9	1.6	0.7	2.4	15.4	2.8	2.5	1.6	2.4	1.2	0.8	0.9	1.4	1.0	0.4	0.5	1.9	2.3	1.8	0.5	0.4	3.2	1.9	0.6	1.0	0.7	1.3	0.3	1.1	0.2	0.1	2.2	0.0	1.0	0.1	0.9	0.0
Macolor macularis	30.4	11.2	8.2	1.5	1.5	3.5	1.3	0.8	10.7	1.9	1.5	1.7	0.8	0.9	1.1	0.8	1.1	0.5	0.6	0.8	7.4	0.8	0.7	1.5	1.5	1.7	0.4	0.5	0.6	2.9	0.1	0.6	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Alepes vari	22.3	6.7	0.4	13.5	2.5	7.1	3.4	0.2	0.5	2.2	1.1	2.1	0.9	13.8	1.1	0.7	1.4	0.1	3.7	0.8	3.1	1.2	0.3	0.6	0.5	0.2	0.9	0.7	0.5	0.6	0.5	0.3	0.1	3.4	0.6	1.3	0.0	0.2	0.6	0.0
Lethrinus rubrioperculatus	20.7	3.9	2.3	1.9	3.2	3.1	2.5	0.6	2.1	4.0	4.1	4.5	5.4	0.6	1.5	3.3	1.7	14.7	4.7	0.6	1.5	0.8	0.1	1.4	0.9	2.2	1.1	0.5	0.5	2.9	0.3	0.9	0.3	0.2	0.0	0.2	0.2	0.2	0.3	0.2
Scarus oviceps	31.0	21.4	2.8	2.6	2.5	3.3	0.7	11.3	1.6	1.7	1.3	0.6	1.5	1.9	2.4	1.8	1.4	0.4	0.6	1.3	0.2	0.4	0.2	1.3	1.1	1.5	0.4	0.2	0.7	0.4	0.2	0.5	0.2	0.0	0.3	0.0	0.1	0.2	0.0	0.1
Naso lituratus	21.5	27.9	6.4	2.6	2.2	3.8	1.6	1.3	1.0	2.7	2.9	3.0	1.9	0.9	1.8	1.2	1.6	0.1	1.1	1.7	2.5	0.3	0.6	1.1	0.7	1.5	0.9	0.1	0.6	0.4	0.3	0.9	2.0	0.1	0.4	0.0	0.1	0.1	0.0	0.3
Centropyge bicolor	19.9	6.3	17.5	5.4	1.5	1.9	1.0	8.0	2.1	2.0	0.9	6.7	2.9	0.5	2.7	0.8	1.4	0.6	0.3	1.5	2.7	2.5	2.4	0.7	0.8	1.4	0.8	0.2	0.3	0.3	0.4	1.2	0.3	0.2	0.0	1.5	0.0	0.1	0.0	0.0
Dasyatis kuhlii	32.7	1.1	0.8	10.2	1.5	1.9	5.3	1.0	2.7	3.3	1.9	1.0	4.7	1.1	3.5	4.9	1.6	0.6	1.8	1.7	0.3	2.7	0.0	1.4	1.0	2.2	1.3	1.7	1.8	0.6	0.2	0.3	0.8	2.3	0.0	0.0	0.0	0.2	0.0	0.0
Balistoides conspicillum	29.9	10.0	3.0	1.1	1.5	1.1	1.4	16.8	2.4	2.9	2.7	2.2	2.5	0.6	1.6	1.7	2.0	0.5	0.6	0.9	2.3	0.4	0.5	1.1	0.9	0.5	0.8	0.5	0.7	1.6	1.2	1.1	0.3	0.0	0.2	0.0	1.8	0.1	0.2	0.0
Lethrinus amboinensis	19.5	19.2	4.2	8.5	0.7	0.7	0.9	1.6	18.8	1.4	1.3	0.7	2.0	2.9	0.6	0.9	0.9	4.5	0.7	0.9	0.4	0.6	0.2	1.1	0.2	1.3	0.4	1.2	0.6	0.3	1.0	0.4	0.2	0.9	0.0	0.0	0.3	0.0	0.0	0.0
all unknown sea snakes pooled	29.6	16.0	1.4	2.1	1.9	5.7	1.0	0.0	1.7	3.3	2.5	1.6	1.3	0.9	2.8	1.6	3.3	1.2	2.5	1.6	0.2	0.8	3.7	1.6	4.8	1.4	0.6	0.0	2.3	0.6	0.4	0.4	0.4	0.2	0.2	0.0	0.0	0.0	0.0	0.0
Gymnosarda unicolor	28.8	0.8	0.8	1.4	6.1	5.2	9.8	0.9	0.9	1.4	4.3	1.2	0.9	5.6	4.1	4.1	1.2	1.5	8.1	0.4	0.4	1.5	0.0	0.9	2.2	1.4	1.1	0.0	1.6	0.3	0.9	0.4	0.3	0.9	0.0	0.0	0.0	0.2	0.5	0.0
Acanthurus leucocheilus	24.8	21.9	6.9	1.1	2.4	1.5	1.2	7.1	0.7	0.8	2.1	1.5	1.2	2.5	1.9	0.8	0.7	1.1	0.4	3.7	2.0	1.2	0.8	1.0	0.7	0.8	1.6	0.5	1.0	0.4	0.6	0.6	0.5	0.1	1.5	0.3	0.0	0.1	2.1	0.0
Carangoides fulvoguttatus	20.8	3.2	0.7	21.1	1.9	1.5	2.6	0.2	6.7	4.1	3.0	0.6	4.2	1.1	0.8	0.5	1.8	0.9	0.4	1.0	0.3	1.1	0.2	4.8	1.0	4.6	1.1	1.4	2.3	0.3	3.4	0.5	0.1	1.3	0.0	0.4	0.0	0.0	0.0	0.0
Lutjanus rivulatus	26.1	22.6	6.6	7.1	1.1	2.3	2.4	0.6	1.2	1.6	0.9	0.9	1.8	1.0	0.5	1.2	1.4	0.7	1.0	1.1	0.4	1.9	0.6	0.7	0.7	0.3	0.5	0.2	0.9	0.6	0.1	0.4	0.4	0.2	5.3	4.2	0.3	0.0	0.0	0.0
Parupeneus multifasciatus	15.8	21.7	31.2	1.2	4.8	1.2	1.7	3.0	0.9	0.9	1.3	1.0	0.8	0.3	1.6	1.7	0.6	0.3	0.2	0.9	0.2	1.7	0.9	0.6	0.6	0.5	0.4	0.5	0.3	0.2	1.0	0.5	0.5	0.1	0.2	0.1	0.8	0.0	0.0	0.0
Naso brachycentron	27.7	15.0	2.0	2.6	1.7	1.3	6.8	3.8	2.0	2.9	2.7	1.2	1.1	1.4	3.3	1.2	1.8	0.9	0.7	3.7	0.3	1.5	1.0	1.9	1.6	1.9	2.9	1.0	1.1	0.5	0.8	0.7	0.2	0.3	0.0	0.2	0.0	0.0	0.1	0.1
Acanthurus olivaceus	17.7	38.9	6.0	2.5	3.7	4.6	1.2	3.3	0.7	0.7	0.8	0.4	1.1	1.2	1.1	3.1	2.7	0.1	0.6	1.2	0.1	0.6	0.8	0.8	0.5	0.5	0.3	0.5	0.7	0.2	0.2	0.6	0.6	0.2	1.7	0.0	0.0	0.0	0.0	0.0
Naso vlamingii	28.2	13.0	14.5	3.4	1.7	3.9	1.3	2.6	4.5	0.9	1.6	3.2	1.3	0.8	1.2	1.4	1.6	0.2	0.7	0.8	4.8	0.6	0.5	0.6	0.2	1.8	0.7	0.3	0.6	1.2	0.2	0.6	0.3	0.0	0.5	0.0	0.0	0.0	0.0	0.0
Parapercis sp1	25.7	18.6	13.7	1.2	2.5	2.6	1.7	3.0	0.9	2.8	1.8	1.2	2.3	0.3	3.0	1.2	1.1	0.2	3.7	1.3	0.2	1.1	1.5	0.8	1.1	0.6	0.6	0.4	1.6	0.1	0.2	0.9	0.5	0.0	0.5	0.6	0.0	0.1	0.1	0.2
Triaenodon obesus	22.0	32.5	2.5	2.2	5.7	1.9	1.6	1.3	2.6	1.6	0.9	1.3	0.7	4.5	1.3	1.2	0.9	0.6	0.8	0.7	0.3	1.0	0.0	0.9	0.7	1.6	0.6	0.6	2.4	0.3	0.1	0.6	1.4	1.7	0.1	0.0	0.1	0.6	0.1	0.0
Caranx melampygus	17.3	10.9	4.2	8.7	3.5	0.9	0.8	0.4	1.6	1.2	1.7	5.2	1.7	2.4	2.7	4.6	2.0	9.1	1.9	0.5	0.1	1.2	0.8	2.0	0.8	1.1	0.7	6.0	0.3	2.3	0.3	0.5	0.6	0.9	0.0	0.0	0.4	0.6	0.0	0.0
Carangoides gymnostethus	20.1	25.2	5.6	4.5	5.0	5.9	2.7	0.8	0.9	2.1	2.5	0.7	0.9	1.1	2.5	1.0	2.1	4.4	1.1	0.9	0.2	0.7	1.2	0.7	0.4	0.7	0.8	0.6	0.3	0.4	1.1	0.3	0.6	0.1	0.0	0.0	0.2	1.5	0.0	0.2
Odonus niger	32.2	11.9	3.4	3.5	1.4	1.5	4.1	1.4	1.6	2.0	2.7	1.2	1.8	4.2	2.0	1.4	1.2	0.4	1.5	2.0	0.9	1.1	1.2	0.6	2.9	0.3	3.3	0.2	0.3	0.2	1.7	0.4	0.9	2.5	2.0	0.0	0.3	0.0	0.0	0.0
Labroides dimidiatus	20.1	5.3	20.2	0.9	6.2	1.3	1.2	7.9	0.3	2.2	3.4	6.6	1.2	0.5	1.2	0.8	1.2	0.4	0.7	1.0	1.6	1.1	0.6	0.5	2.1	0.6	2.1	1.0	0.7	2.4	0.2	0.7	0.3	2.4	0.7	0.2	0.0	0.1	0.1	0.0

Species	Predictor variables ranked from left to right in decreasing, average influence																																							
	asp.dir	depth	calc.rf	lat	lon	spilldist	compass	mssv.crl	grvl	hyp5	curv	bare	slp	rbbl	hyp50	hyp25	hyp10	sndy	oilhours	std50	sft.crl	rng50	sol.crl	rng5	rng25	std5	std25	shoalarea	rng10	visibility	encr	std10	spng	hlmda	bldr	mcralg	fans	newoiladj	whps	hyd
Naso brevirostris	27.4	23.0	7.8	4.9	1.4	3.3	1.3	0.8	0.2	2.5	1.5	0.8	3.4	1.2	1.1	0.9	1.8	1.2	1.1	1.3	2.4	0.4	0.2	0.9	0.7	1.0	1.8	0.4	0.7	2.6	0.2	1.1	0.2	0.1	0.4	0.0	0.0	0.1	0.2	0.0
Parupeneus cyclostomus	36.8	3.3	1.4	4.1	12.0	1.8	2.0	0.5	2.1	2.0	2.3	1.2	2.6	0.7	3.0	1.5	2.0	0.3	0.7	0.8	2.3	1.7	2.2	2.2	0.3	0.8	0.8	0.5	1.2	0.6	0.4	0.8	0.5	0.6	1.3	1.0	0.3	1.3	0.0	0.0
Scolopsis xenochrous	23.9	6.3	8.5	3.8	1.2	2.6	1.3	2.4	0.4	6.7	4.0	3.6	3.3	1.4	1.0	3.6	1.7	0.6	1.4	1.4	0.6	0.9	7.5	0.6	0.8	1.4	1.3	0.4	1.4	0.9	0.4	2.1	0.3	0.5	0.4	0.4	1.0	0.1	0.0	0.0
Siganus argenteus	30.2	5.1	0.2	5.0	5.2	2.6	2.4	0.0	1.9	2.3	1.2	1.2	1.3	0.7	4.4	3.0	3.1	0.9	1.6	1.0	1.7	1.3	7.0	2.7	0.8	0.8	1.2	4.4	1.1	2.3	0.4	1.1	0.1	0.6	0.7	0.6	0.1	0.0	0.0	0.0
Pomacanthus imperator	21.5	16.6	15.1	3.2	3.4	3.6	1.7	9.3	4.1	1.3	1.6	3.8	1.3	1.1	0.5	0.7	1.3	0.2	0.8	0.6	0.4	0.7	0.4	0.6	0.8	1.0	0.3	0.7	0.3	0.1	0.5	0.4	0.6	1.1	0.1	0.0	0.1	0.0	0.0	0.0
Apolemichthys trimaculatus	22.7	12.7	13.8	2.6	4.5	4.2	3.4	1.2	2.3	2.9	1.0	3.0	1.1	0.7	1.5	3.2	2.0	1.4	0.7	0.7	2.0	1.0	2.2	1.3	1.0	1.3	0.6	0.3	1.1	0.6	0.2	0.7	1.6	0.1	0.2	0.1	0.0	0.0	0.0	0.0
Aipysurus laevis	28.2	24.0	3.4	1.8	4.4	2.3	1.9	2.1	1.3	3.0	2.5	0.6	2.9	1.1	3.0	2.2	2.5	0.5	0.7	0.9	0.1	0.7	0.3	1.4	0.7	0.4	1.2	0.4	0.5	0.6	0.7	0.8	1.9	0.3	0.2	0.0	0.1	0.2	0.0	0.0
Zanclus cornutus	30.1	10.3	9.5	1.5	4.3	2.6	1.5	2.7	2.2	3.2	4.1	5.8	1.2	0.7	1.4	1.8	2.3	1.5	1.2	1.1	1.8	0.6	0.4	0.7	0.8	0.7	0.7	0.6	0.5	0.2	0.3	0.5	1.3	0.7	1.0	0.0	0.1	0.0	0.2	0.0
Carangoides orthogrammus	20.7	2.5	5.3	21.0	3.8	3.1	3.0	0.5	4.8	1.3	1.2	2.3	3.1	1.9	2.7	1.8	2.2	1.9	0.7	1.8	1.2	2.4	0.5	0.8	1.9	0.7	2.6	0.5	0.9	0.2	0.4	0.8	0.3	0.1	0.2	0.3	0.2	0.3	0.0	0.0
Pomacentrus coelestis	23.4	32.6	8.8	4.6	0.9	1.4	1.4	0.3	0.4	1.6	1.5	1.4	0.8	2.8	1.1	1.5	1.5	0.9	0.7	1.4	0.7	0.4	2.6	0.4	0.2	0.6	0.6	0.2	0.7	0.4	0.2	0.5	0.2	3.3	0.0	0.0	0.0	0.1	0.0	0.0
Balistoides viridescens	26.6	20.3	9.4	3.7	4.1	4.3	2.6	2.8	0.5	2.4	2.4	1.5	1.4	0.9	0.7	0.7	1.5	0.1	0.3	2.9	0.9	0.7	0.0	1.6	0.9	0.9	0.4	0.7	0.3	0.4	0.3	0.3	1.8	0.1	0.4	0.0	0.7	0.0	0.5	0.0
Naso hexacanthus	23.5	25.2	4.1	1.6	10.2	4.0	1.0	0.4	2.7	2.8	1.6	0.7	1.1	2.7	1.3	2.2	2.2	0.7	1.1	1.1	0.7	1.4	0.4	1.4	0.8	0.9	0.7	0.8	0.6	0.2	0.2	0.7	0.1	0.7	0.0	0.0	0.1	0.1	0.1	0.0
Acanthurus grammoptilus	24.0	14.2	10.9	8.2	2.5	2.3	6.3	1.3	0.7	2.2	1.6	0.9	1.7	1.3	1.1	0.9	1.0	1.3	1.2	1.9	0.6	0.8	1.1	0.8	0.8	2.0	1.8	1.9	0.6	0.6	0.7	1.5	0.5	0.1	0.6	0.0	0.0	0.1	0.1	0.0
Lethrinus atkinsoni	19.8	27.6	2.7	10.0	2.2	5.7	1.4	2.4	1.2	1.0	1.6	1.8	0.5	0.7	0.8	1.2	1.6	3.6	5.3	1.8	0.2	1.0	0.1	0.5	0.4	0.4	0.5	0.7	0.8	0.2	0.4	0.3	0.2	0.9	0.0	0.0	0.2	0.3	0.0	0.1
Sufflamen fraenatum	34.9	1.8	0.4	3.9	2.6	3.1	1.3	0.3	2.4	4.8	1.6	1.1	2.4	2.1	2.4	1.6	1.9	0.5	1.3	1.2	0.5	3.2	3.8	1.2	2.7	2.3	2.3	0.7	1.8	1.4	3.5	1.4	1.9	0.1	0.9	0.1	0.1	0.2	0.0	0.0
Variola albimarginata	24.5	8.3	19.5	1.0	4.8	3.2	3.2	1.3	0.5	1.5	1.7	5.8	2.1	0.7	0.6	1.3	1.0	0.6	1.1	0.6	2.9	1.4	3.6	0.7	1.6	0.7	0.8	0.6	0.5	0.3	0.4	0.8	0.3	1.1	0.0	0.0	0.4	0.1	0.3	0.0
Aprion virescens	34.3	10.2	0.7	4.2	4.8	2.1	1.4	0.4	1.3	0.9	1.3	2.6	2.2	1.5	1.9	1.3	3.5	1.2	0.9	0.9	4.8	2.0	3.1	2.7	0.7	0.9	1.2	0.6	1.1	1.3	0.1	1.1	1.0	0.1	0.0	0.6	0.0	0.1	0.9	0.0
Carcharhinus amblyrhynchos	26.5	23.5	1.1	5.9	2.9	1.5	3.8	0.9	2.8	3.3	3.1	1.0	1.6	0.6	2.3	1.8	1.2	1.1	0.6	0.7	0.9	1.3	0.5	1.7	1.3	1.1	0.8	0.8	1.2	0.4	0.3	0.7	0.4	1.0	0.0	0.0	0.9	0.1	0.0	0.2
Elagatis bipinnulata	32.3	2.5	0.9	1.3	6.4	2.2	8.5	0.1	1.4	2.2	2.7	0.6	2.5	5.9	1.8	1.2	2.4	2.5	1.3	1.9	0.8	2.7	0.6	1.0	2.5	1.0	0.9	1.5	3.8	1.3	1.2	1.1	0.2	0.7	0.0	0.0	0.0	0.1	0.1	0.1
Gymnocranius grandoculis	27.3	6.0	7.3	6.7	3.7	1.8	1.7	0.1	8.8	2.3	3.2	4.6	1.5	1.3	2.3	1.5	2.1	0.7	0.7	1.1	1.7	1.7	1.5	0.8	1.0	0.7	0.4	3.2	1.0	1.0	0.1	0.9	0.5	0.3	0.0	0.0	0.0	0.1	0.0	0.1
Echeneis naucrates	38.2	4.6	6.9	8.3	5.0	3.5	7.9	0.0	0.0	0.0	3.6	0.0	3.3	0.0	0.0	0.0	0.0	0.0	8.0	0.0	2.4	0.0	0.0	0.0	2.3	0.0	0.0	0.0	0.0	2.6	0.0	0.0	3.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Lethrinus olivaceus	32.0	20.1	1.1	2.4	2.3	1.8	1.4	0.5	4.6	1.6	2.0	1.5	1.6	3.5	2.4	3.9	0.9	3.6	1.1	0.9	0.1	0.9	0.2	0.7	0.5	0.8	0.7	0.9	0.5	1.0	1.8	0.6	0.8	0.6	0.0	0.1	0.2	0.1	0.0	0.0
Cirrhilabrus sp1	32.4	2.6	2.0	1.8	6.7	3.5	1.5	1.8	1.2	2.1	1.5	1.6	2.5	6.4	2.0	2.6	1.1	2.0	2.7	0.5	0.1	1.2	2.6	2.2	1.3	3.5	0.8	0.2	2.8	0.4	2.6	1.3	0.6	1.7	0.2	0.1	0.0	0.0	0.0	0.0

Appendix 4.5 Linear regression-GAMMS analysis Tables.

Table A4.5.1. Results of PERMANOVA testing for differences among shoals.

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms
Shoal	8	11.798	1.4747	6.4527	0.0001	9891
Residual	239	54.622	0.22854			
Total	247	66.419				

Shoal on SR

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms
Shoal	8	8750.7	1093.8	4.6187	0.001	999
Res	239	56602	236.83			
Total	247	65353				

Table A4.5.2: Significance values for pairwise comparisons of shoals based on PERMANOVA for biotic habitat predicted from multibeam ; Bold values are statistically significant at p<0.05

Shoal:	BAE	BAW	ECH	EUG	GOE	HEY	SHE	VUL
BAW	0.0193							
ECH	0.0138	0.0001						
EUG	0.14	0.0044	0.0041					
GOE	0.0425	0.46	0.0001	0.0173				
HEY	0.0613	0.0043	0.0001	0.1	0.0144			
SHE	0.0001	0.0046	0.0001	0.0001	0.0035	0.0001		
VUL	0.16	0.0019	0.0225	0.2111	0.0028	0.26	0.0001	
WGB	0.001	0.0004	0.0001	0.0001	0.0008	0.0001	0.0001	0.0001

Table A4.5.3. Correlation coefficients between exposure metrics and habitat variables with red indicating correlation coefficients greater than 0.5, black indicating values between 0.3 and 0.5 and grey indicating correlations less than 0.3. Bolded numbers are those for variables used in the models.

	Variable	*abbreviation*	*Lat*	*Long*	*Bearing from True North(°)*	*distsp*	*newoiladj*	*Minimum Hours Oil Exposure*	*Maximum Hours Oil Exposure*
exposure metrics	latitude	lat	1						
	longitude	long	0.07	1					
	bearing from true north	bearing	0.78	-0.44	1				
	distance	dist	-0.76	-0.67	-0.30	1			
	sediment hydrocarbon concentration	[HC]	0.35	0.61	0.05	-0.70	1		
	minimum hours exposure	minhrs	0.20	0.47	-0.08	-0.58	0.79	1	
	maximum hours exposure	maxhrs	0.20	0.47	-0.08	-0.58	0.79	1.00	1
	area	area	-0.69	-0.13	-0.50	0.50	-0.34	-0.21	-0.21
	depth	**depth**	**0.24**	**-0.02**	**0.13**	**-0.14**	**-0.05**	**-0.08**	**-0.08**
towed video	Sum of algae	ALG	0.19	0.15	-0.02	-0.14	0.02	-0.24	-0.24
	Sum of hard corals	HC	-0.47	-0.14	-0.39	0.45	-0.30	0.05	0.05
	Sum of others	OTH	0.24	-0.09	0.36	-0.25	0.21	0.22	0.22
	Sum of soft corals	SC	0.08	-0.14	0.29	0.09	-0.22	-0.17	-0.17
abiota from BRUVS	**Sum of sponges**	**SP**	**-0.45**	**0.29**	**-0.64**	**0.25**	**0.00**	**-0.07**	**-0.07**
	%Boulder	B	-0.05	-0.06	-0.01	0.06	-0.12	-0.09	-0.09
	%Calcareous Reef	**CR**	**-0.12**	**0.05**	**-0.14**	**0.07**	**-0.13**	**-0.05**	**-0.05**
	%Gravel	G	0.30	-0.18	0.33	-0.10	0.12	0.05	0.05
	%Indeterminant	IND	-0.03	0.07	-0.09	-0.01	-0.05	-0.06	-0.06
	%Rubble	R	-0.24	0.13	-0.26	0.10	0.02	0.02	0.02
	%Sand	S	0.01	0.06	0.01	-0.07	0.04	0.03	0.03
biota from BRUVS	%bryozoans	br	-0.05	0.11	-0.07	0.01	0.16	-0.06	-0.06
	%sea fans	f	0.19	-0.05	0.20	-0.09	-0.14	-0.09	-0.09
	%halimeda	hal	0.02	-0.08	-0.04	0.03	0.05	0.14	0.14
	%hard coral	hc	-0.08	0.02	-0.07	0.06	-0.15	-0.10	-0.10
	%hard coral solitary	hcs	-0.01	-0.18	-0.02	0.13	-0.14	-0.09	-0.09
	%hydroids	hyd	-0.15	0.00	-0.11	0.13	-0.08	-0.08	-0.08
	%macroalgae	mac	-0.08	0.02	-0.08	0.02	-0.02	0.03	0.03
	%no biota	none	0.06	-0.06	0.16	-0.06	0.10	0.09	0.09
	%soft corals	sc	0.01	0.20	-0.12	-0.07	0.04	-0.08	-0.08
	%sponge	sp	0.03	0.09	0.00	-0.07	-0.01	0.09	0.09
	%sea whips	w	-0.10	0.04	-0.12	0.06	-0.07	-0.08	-0.08
	%zoanthids	z	0.02	0.07	-0.03	-0.07	0.06	0.11	0.11
multibeam physical attributes	depth multibeam	depthMB	-0.26	0.03	-0.14	0.14	0.06	0.09	0.09
	aspect	asp	0.02	-0.08	0.07	0.05	-0.08	-0.11	-0.11
	curvature	curv	0.04	0.04	0.03	-0.07	0.08	0.08	0.08
	hyp10 -Radford to confirm	hyp10	0.02	0.05	-0.03	-0.05	0.07	0.10	0.10
	hyp25	hyp25	0.15	-0.07	0.14	-0.07	0.00	0.07	0.07
	hyp5	hyp5	-0.03	0.06	-0.06	-0.03	0.07	0.08	0.08
	hyp50	hyp50	0.28	-0.15	0.29	-0.10	-0.06	0.01	0.01
	plan	plan	0.03	0.03	0.03	-0.05	0.07	0.07	0.07

	profile	prof	-0.05	-0.05	-0.02	0.09	-0.08	-0.09	-0.09
	rng10	rng10	0.19	0.01	0.14	-0.12	-0.08	-0.01	-0.01
	rng25	rng25	0.22	-0.03	0.18	-0.12	-0.09	-0.03	-0.03
	rng5	rng5	0.19	0.01	0.13	-0.13	-0.06	0.01	0.01
	rng50	rng50	0.28	-0.08	0.25	-0.13	-0.10	-0.05	-0.05
	slp	slp	0.18	0.03	0.12	-0.14	-0.04	0.04	0.04
	std10	std10	0.20	0.02	0.13	-0.13	-0.07	0.00	0.00
	std25	std25	0.22	-0.01	0.16	-0.13	-0.08	-0.02	-0.02
	std5	std5	0.19	0.02	0.12	-0.13	-0.06	0.02	0.02
	std50	std50	0.26	-0.06	0.22	-0.13	-0.10	-0.04	-0.04
predicted biota from multibeam	FilterFeeders	FilterFeeders	0.21	0.06	0.18	-0.16	0.15	-0.05	-0.05
	Halimeda	Halimeda	0.19	0.02	0.20	-0.14	0.18	0.03	0.03
	HardCoral	HardCoral	-0.05	-0.10	0.01	0.11	-0.07	-0.04	-0.04
	Isolates	Isolates	0.18	-0.10	0.21	-0.07	-0.08	-0.06	-0.06
	Macroaglae	Macroaglae	0.14	0.06	0.17	-0.13	0.18	-0.01	-0.01
	SoftCoral	SoftCoral	0.15	0.11	0.09	-0.14	0.11	-0.06	-0.06
	LimestoneHighRelief	LimestoneHighRelief	-0.13	0.04	-0.10	0.08	-0.03	0.02	0.02
	LimestoneLowRelief	LimestoneLowRelief	-0.33	0.06	-0.27	0.22	-0.10	0.00	0.00
	None	None	-0.03	0.04	-0.01	0.02	0.03	-0.03	-0.03
	RubbleStone	RubbleStone	-0.20	-0.07	-0.13	0.17	-0.06	0.02	0.02
	Rubble	Rubble	-0.06	0.11	-0.11	-0.03	0.06	0.06	0.06
	Sand	Sand	-0.09	0.00	-0.09	0.06	-0.06	-0.05	-0.05
	CoarseSand	CoarseSand	0.35	0.04	0.35	-0.27	0.18	-0.02	-0.02
	SandRubble	SandRubble	0.35	-0.21	0.31	-0.12	-0.06	-0.06	-0.06
	SandWaves	SandWaves	0.06	-0.02	0.08	-0.03	-0.05	-0.03	-0.03
	Silt	Silt	0.04	0.14	-0.07	-0.10	0.01	0.01	0.01

Table A4.5.4. Descriptive statistics for species richness, total abundance, mean length and biomass by shoal and for all shoals

	BAE	BAW	ECH	EUG	GOE	HEY	SHE	VUL	WGB	All Shoals
Species Richness										
Mean	29.9	25.2	37.5	30.8	21.0	23.6	15.9	23.4	18.9	25.3
SE	2.4	4.1	2.9	3.2	2.6	2.0	1.5	2.1	1.7	0.9
Minimum	3	5	7	11	9	1	8	10	8	1
Maximum	54	71	65	62	55	55	39	52	37	71
Total Abundance										
Mean	110.9	78.3	137.4	153.4	86.3	85.8	77.2	84.1	112.7	100.5
SE	12.0	16.1	12.0	21.7	10.1	9.9	12.2	10.7	32.9	5.0
Minimum	18	9	38	32	25	2	17	27	24	2
Maximum	300	349	251	377	235	491	288	219	578	578
Mean Length										
Mean	308.8	315.8	286.9	310.6	323.1	283.6	305.7	339.3	289.3	303.8
SE	13.3	14.0	11.6	13.2	11.1	10.7	14.4	17.5	12.9	4.6
Minimum	171.2	212.1	183.3	215.4	242.7	60.5	116.9	191.4	140.9	60.5
Maximum	516.4	458.3	375.5	441.2	437.9	488.6	443.6	473.0	394.6	516.4
Biomass										
Mean	111.8	94.9	105.5	108.0	70.7	68.1	86.6	109.2	85.2	90.3
SE	14.0	15.0	13.9	18.5	10.1	8.3	17.4	12.4	32.7	4.9
Minimum	16.5	5.7	29.3	9.7	11.4	0.01	2.5	12.5	12.9	0.01
Maximum	361.5	266.6	304.2	368.0	196.4	326.5	292.5	238.7	547.0	547.0
Sea snake abundance										
Mean	0.67	0.68	0.67	0.08	0.35	0.45	0.04	0.92	0.31	0.47
SE	0.17	0.14	0.12	0.06	0.13	0.08	0.04	0.19	0.12	0.04
Minimum	0	0	0	0	0	0	0	0	0	0
Maximum	4	2	2	1	2	2	1	3	1	4

Table A4.5.5. Results of GAMMS for species richness (SR), total abundance (TA), mean length (FL), and biomass (B).

Model	R-sq (adj)	AIC	Habitat p-value	Depth p-value	Oil p-value	lat	long
SR = CR + Depth	0.562	1846.845	**<0.0001**	**<0.0001**			
SR = CR + Depth + pres.oil	0.56	1848.555	**<0.0001**	**<0.0001**	0.591		
SR = CR + Depth + dist.spill	0.565	1848.633	**<0.0001**	**<0.0001**	0.126		
SR = CR + Depth + Minimum.Hours.Oil.Exposure	0.566	1847.908	**<0.0001**	**<0.0001**	**0.083**		
SR = CR + Depth + lat +long + Minimum.Hours.Oil.Exposure	0.584	1851.897	**<0.0001**	**<0.0001**	0.149	0.1507	**0.0125**
SR = CR + Depth + lat +long	0.583	1849.923	**<0.0001**	**<0.0001**		0.1219	**0.0108**
TA = CR + Depth	0.136	2844.146	**<0.0001**	**0.0715**			
TA = CR + Depth + pres.oil	0.134	2846.129	**<0.0001**	**0.0733**	0.894		
TA = CR + Depth + dist.spill	0.135	2847.325	**<0.0001**	**0.0852**	0.3633		
TA = CR + Depth + Minimum.Hours.Oil.Exposure	0.137	2847.354	**<0.0001**	**0.0662**	0.3637		
meanFL = CR	0.0974	2773.733	**<0.0001**				
meanFL = CR + Depth	0.0942	2777.614	**<0.0001**	0.731			
meanFL = CR + pres.oil	0.112	2773.472	**<0.0001**		0.105		
meanFL = CR + dist.spill	0.136	2771.304	**<0.0001**		**0.000627**		
meanFL = CR + Minimum.Hours.Oil.Exposure	0.121	2773.908	**<0.0001**		**0.023**		
Biomass = CR + Depth	0.0861	749.3239	**0.135943**	**0.00091**			
Biomass = Depth	0.0821	747.5356		**0.000282**			
Biomass = Depth + pres.oil	0.0953	748.2072		**0.000175**	0.215		
Biomass = Depth + dist.spill	0.109	749.9285		**<0.0001**	**0.0793**		
Biomass = Depth + Minimum.Hours.Oil.Exposure	0.0851	751.11		**0.0003**	0.4999		
SppD = Depth	0.295	614.6752	**<0.0001**				
SppD = Depth + pres.oil	0.368	613.2521	**<0.0001**	**0.0427**			
SppD = Depth + dist.spill	0.394	616.2488	**<0.0001**	**0.0232**			
SppD = Depth + Minimum.Hours.Oil.Exposure	0.406	612.412	**<0.0001**	**0.00203**			
SppK = SandRubble	0.296	753.3217	**<0.0001**				
SppK = SandRubble + pres.oil	0.297	754.0279	**<0.0001**	0.257			
SppK = SandRubble + dist.spill	0.312	750.4224	**<0.0001**	**0.0121**			
SppK = SandRubble + Minimum.Hours.Oil.Exposure	0.3	755.0209	**<0.0001**	0.13			

Table A4.5.6. Linear regressions for univariate metrics based on habitat and habitat + exposure.

	Habitat				Habitat + Exposure				
	Estimate	SE	t	p		Estimate	SE	t	p
Species richness:									
Intercept	14.8215	2.3822	6.222	0.000436	(Intercept)	12.01528	2.36724	5.076	0.00228
CR	0.5112	0.104	4.913	0.001726	CR	0.47567	0.08699	5.468	0.00156
					dist	0.05075	0.02417	2.099	0.08055
	F-statistic:	24.14	*p-value:*	0.001726		*F-statistic:*	20.15	*p-value:*	0.002176
	RSE	3.371	*R2*	0.78		*RSE*	2.765	*R2*	0.87
			R2adj	0.74				*R2adj*	0.83
Total abundance									
(Intercept)	42.5	11.65	3.649	0.00819	(Intercept)	50.646	9.806	5.165	0.002084
SP	860.63	154.69	5.564	0.000848	SP	853.358	121.564	7.02	0.000417
					Hcnewadj	-94.295	40.797	-2.311	0.060158
	F-statistic:	30.95	p-value:	0.008477		F-statistic:	27.75	p-value:	0.009287
	RSE	12.66	R2	0.8156		RSE	9.945	R2	0.902
			R2adj	0.7892				R2adj	0.8699
MeanFL									
(Intercept)	288.736	4.428	65.202	5.24E-11	(Intercept)	282.797	3.194	88.541	1.40E-10
prof	-34.389	8.779	-3.917	0.00577	prof	-21.777	6.459	-3.371	0.015
					oil	117.512	33.152	3.545	0.0122
	F-statistic:	15.34	p-value:	0.00577		F-statistic:	26.63	p-value:	0.001038
	RSE	10.99	R2	0.6867		RSE	6.747	R2	0.8987
			R2adj	0.642				R2adj	0.865
Biomass	weak				not significant so not included				

Table A4.5.7: Results of logistic regressions between the presence/absence of sea snakes, habitat and exposure variables

Coefficients:					
	Estimate	Std. Error	z value	Pr(>|z|)	
(Intercept)	286.1969	92.43708	3.096	0.00196	**
depth	-0.10237	0.02019	-5.069	4.00E-07	***
ALG	-9.97322	3.52045	-2.833	0.00461	**
Long	-2.24353	0.74398	-3.016	0.00256	**

Null deviance	331.05	df	247		
Residual deviance: 258.10 on 244 degrees of freedom	258.1	df	244		
AIC	266.1				

Appendix 1. Metadata location and description of sampling locations for BRUVS, towed video transects, sediment collection and multibeam surveys

Date	Time	Technique	Site	Sample	Lat_start	Long_start	DepthStart	Lat_end	Long_end	DepthEnd
17/03/11	6:51	Sediment	Eug (North)	GA001	-13.044	124.5829				
17/03/11	7:19	Sediment	Eug (East)	GA002	-13.079	124.6295				
17/03/11	8:41	Sbruvs	Eug1		-13.079	124.5949	45.8			
17/03/11	8:58	Sbruvs	Eug2		-13.076	124.5902	30.6			
17/03/11	9:04	Sbruvs	Eug3		-13.075	124.5858	25.2			
17/03/11	9:10	Sbruvs	Eug4		-13.072	124.5760	21.2			
17/03/11	9:16	Sbruvs	Eug5		-13.077	124.5762	21.1			
17/03/11	9:21	Sbruvs	Eug6		-13.076	124.5802	20.4			
17/03/11	9:25	Sbruvs	Eug7		-13.079	124.5842	22.3			
17/03/11	9:32	Sbruvs	Eug8		-13.084	124.5904	34.6			
17/03/11	11:49	Towcam	Eug1		-13.079	124.5955	49.3	-13.075	124.5889	28.1
17/03/11	12:20	Towcam	Eug2		-13.075	124.5904	30.5	-13.071	124.5822	24
17/03/11	13:20	Towcam	Eug3		-13.071	124.5819	23.8	-13.066	124.5730	59.8
17/03/11	13:53	Sbruvs	Eug9		-13.070	124.5701	35.1			
17/03/11	13:58	Sbruvs	Eug10		-13.075	124.5693	34.2			
17/03/11	14:00	Sbruvs	Eug11		-13.078	124.5701	40.5			
17/03/11	14:04	Sbruvs	Eug12		-13.081	124.5752	32.7			
17/03/11	14:07	Sbruvs	Eug13		-13.083	124.5781	30.9			
17/03/11	14:11	Sbruvs	Eug14		-13.084	124.5833	29.5			
17/03/11	14:15	Sbruvs	Eug15		-13.087	124.5920	51.7			
17/03/11	14:20	Sbruvs	Eug16		-13.082	124.5953	51			
17/03/11	16:22	Towcam	Eug4		-13.083	124.5951	49.9	-13.079	124.5887	26.2
17/03/11	16:51	Towcam	Eug5		-13.080	124.5890	26.9	-13.076	124.5825	20.4
17/03/11	17:17	Towcam	Eug6		-13.076	124.5831	21.6	-13.072	124.5772	19
17/03/11	17:47	Towcam	Eug7		-13.072	124.5767	19.5	-13.067	124.5685	59.6
17/03/11	O/N	Multibeam	Eug		-13.075	124.5799				
18/03/11	6:24	Sediment	Eug (South)	GA003	-13.100	124.5843				
18/03/11	6:52	Sediment	Eug (West)	GA004	-13.076	124.5463				
18/03/11	7:51	Sbruvs	Eug17		-13.065	124.5750	60.8			
18/03/11	7:57	Sbruvs	Eug18		-13.065	124.5791	59.1			
18/03/11	8:07	Sbruvs	Eug20		-13.068	124.5831	34.7			
18/03/11	8:12	Sbruvs	Eug21		-13.071	124.5881	33.8			
18/03/11	8:17	Sbruvs	Eug22		-13.069	124.5911	60.5			
18/03/11	8:24	Sbruvs	Eug23		-13.075	124.5950	51.2			
18/03/11	8:35	Sbruvs	Eug24		-13.069	124.5866	40.4			
18/03/11	8:51	Sbruvs	Eug19		-13.068	124.5773	32.1			
18/03/11	10:19	Towcam	Eug8		-13.066	124.5820	51.8	-13.071	124.5891	37.8
18/03/11	10:52	Towcam	Eug9		-13.070	124.5886	42.9	-13.073	124.5953	61.3
18/03/11	11:33	Towcam	Eug10		-13.086	124.5920	43.3	-13.082	124.5840	22.4
18/03/11	12:12	Towcam	Eug11		-13.081	124.5836	21.9	-13.076	124.5745	21.9
18/03/11	13:22	Towcam	Eug12		-13.076	124.5749	20.6	-13.071	124.5684	36.6
18/03/11	13:53	Towcam	Eug13		-13.078	124.5715	31	-13.080	124.5728	33.2
18/03/11	14:12	Towcam	Eug14		-13.076	124.5669	46.5	-13.075	124.5772	18.2
18/03/11	14:50	Towcam	Eug15		-13.075	124.5747	19.5	-13.075	124.5881	25.5
18/03/11	15:37	Towcam	Eug16		-13.073	124.5855	24.1	-13.072	124.5954	64
18/03/11	16:16	Towcam	Eug17		-13.087	124.5923	47.2	-13.080	124.5896	28.1
18/03/11	16:47	Towcam	Eug18		-13.082	124.5881	26.5	-13.073	124.5817	21
18/03/11	17:22	Towcam	Eug19		-13.074	124.5821	21.3	-13.066	124.5765	39.7

18/03/11	O/N	Multibeam	Eug		-13.075	124.5799				
18/03/11	O/N	Multibeam	Goe		-12.883	124.3434				
21/03/11	5:03	Sediment	Montara Well Head	GA005	-12.687	124.5220				
21/03/11	5:22	Sediment	Montara Well Head	GA006	-12.689	124.5567				
21/03/11	5:41	Sediment	Montara Well Head	GA007	-12.653	124.5565				
21/03/11	6:01	Sediment	Montara Well Head	GA008	-12.655	124.5194				
21/03/11	6:24	Sediment	Montara Well Head	GA009	-12.709	124.4977				
21/03/11	6:38	Sediment	Montara Well Head	GA010	-12.725	124.4778				
21/03/11	6:52	Sediment	Montara Well Head	GA011	-12.742	124.4537				
21/03/11	7:04	Sediment	Montara Well Head	GA012	-12.758	124.4316				
21/03/11	7:20	Sediment	Montara Well Head	GA013	-12.775	124.4093				
21/03/11	7:34	Sediment	Montara Well Head	GA014	-12.791	124.3874				
21/03/11	7:49	Sediment	Montara Well Head	GA015	-12.808	124.3643				
21/03/11	8:03	Sediment	Montara Well Head	GA016	-12.824	124.3430				
21/03/11	8:28	Sediment	Montara Well Head	GA017	-12.840	124.3208				
21/03/11	9:00	Sbruvs	Goe1		-12.877	124.3431	39.9			
21/03/11	9:04	Sbruvs	Goe2		-12.878	124.3508	44.5			
21/03/11	9:08	Sbruvs	Goe3		-12.883	124.3515	39.8			
21/03/11	9:11	Sbruvs	Goe4		-12.886	124.3509	38.5			
21/03/11	9:15	Sbruvs	Goe5		-12.888	124.3482	33.2			
21/03/11	9:18	Sbruvs	Goe6		-12.889	124.3439	32.8			
21/03/11	9:25	Sbruvs	Goe7		-12.883	124.3463	34			
21/03/11	9:30	Sbruvs	Goe8		-12.880	124.3441	34.4			
21/03/11	11:58	Towcam	Goe1		-12.889	124.3383	68.2	-12.889	124.3383	69.8
21/03/11	12:19	Towcam	Goe2		-12.884	124.3334	40.1	-12.880	124.3404	33.9
21/03/11	13:31	Towcam	Goe3		-12.880	124.3399	31	-12.876	124.3473	52.8
21/03/11	14:06	Sbruvs	Goe9		-12.878	124.3475	36.6			
21/03/11	14:09	Sbruvs	Goe10		-12.881	124.3487	36.1			
21/03/11	14:13	Sbruvs	Goe11		-12.884	124.3500	37			
21/03/11	14:18	Sbruvs	Goe12		-12.887	124.3449	32			
21/03/11	14:21	Sbruvs	Goe13		-12.887	124.3397	31			
21/03/11	14:24	Sbruvs	Goe14		-12.882	124.3404	26.1			
21/03/11	14:27	Sbruvs	Goe15		-12.880	124.3399	30.7			
21/03/11	14:29	Sbruvs	Goe16		-12.877	124.3390	38.8			
21/03/11	16:18	Towcam	Goe4		-12.876	124.3453	40.7	-12.891	124.3459	70.2
21/03/11	17:11	Towcam	Goe5		-12.884	124.3391	20.3	-12.880	124.3347	33.3
21/03/11	17:39	Towcam	Goe6		-12.880	124.3341	33.3	-12.878	124.3325	69.5
21/03/11	O/N	Multibeam	Goe		-12.883	124.3434				
22/03/11	7:03	Sediment	Montara Well Head	GA018	-12.855	124.2971				
22/03/11	7:17	Sediment	Montara Well Head	GA019	-12.871	124.2741				
22/03/11	8:10	Sediment	Goe (West)	GA020	-12.889	124.3282				
22/03/11	8:18	Sediment	Goe (South)	GA021	-12.897	124.3421				
22/03/11	8:37	Sediment	Goe (East)	GA022	-12.869	124.3415				
22/03/11	8:52	Sediment	Goe (North)	GA023	-12.882	124.3574				
22/03/11	9:00	Sbruvs	Goe17		-12.879	124.3335	39.2			
22/03/11	9:03	Sbruvs	Goe18		-12.881	124.3354	28.3			
22/03/11	9:05	Sbruvs	Goe19		-12.883	124.3332	38.1			
22/03/11	9:10	Sbruvs	Goe20		-12.884	124.3371	25			
22/03/11	9:13	Sbruvs	Goe21		-12.886	124.3375	31.7			
22/03/11	9:16	Sbruvs	Goe22		-12.886	124.3346	46.4			

22/03/11	9:22	Sbruvs	Goe23		-12.889	124.3403	43			
22/03/11	9:25	Sbruvs	Goe24		-12.885	124.3432	33.8			
22/03/11	11:26	Towcam	Goe7		-12.881	124.3427	35.9	-12.881	124.3309	64.7
22/03/11	13:23	Towcam	Goe8		-12.881	124.3420	36.3	-12.881	124.3537	66.8
22/03/11	14:05	Towcam	Goe9		-12.881	124.3461	36.3	-12.890	124.3400	76
22/03/11	15:00	Towcam	Goe10		-12.882	124.3482	35.6	-12.891	124.3429	78.7
22/03/11	15:46	Towcam	Goe11		-12.878	124.3438	34.8	-12.878	124.3331	56.3
22/03/11	16:56	Towcam	Goe12		-12.878	124.3432	32.9	-12.879	124.3528	59.2
23/03/11	5:58	Sediment	Vul (North)	GA024	-12.784	124.2819				
23/03/11	6:30	Sediment	Vul (West)	GA025	-12.803	124.2383				
23/03/11	7:12	Sediment	Vul (South)	GA026	-12.828	124.2782				
23/03/11	7:55	Sbruvs	Vul1		-12.798	124.3043	42.5			
23/03/11	7:58	Sbruvs	Vul2		-12.797	124.3008	40.6			
23/03/11	8:03	Sbruvs	Vul3		-12.796	124.2926	38.4			
23/03/11	8:08	Sbruvs	Vul4		-12.795	124.2847	32.5			
23/03/11	8:13	Sbruvs	Vul5		-12.795	124.2751	30.4			
23/03/11	8:20	Sbruvs	Vul6		-12.798	124.2705	21.9			
23/03/11	8:24	Sbruvs	Vul7		-12.794	124.2652	32.1			
23/03/11	8:28	Sbruvs	Vul8		-12.796	124.2594	31.2			
23/03/11	10:11	Sbruvs	Vul9		-12.803	124.3097	46.2			
23/03/11	10:15	Sbruvs	Vul10		-12.808	124.3008	22.1			
23/03/11	10:20	Sbruvs	Vul11		-12.804	124.2928	24.7			
23/03/11	10:23	Sbruvs	Vul12		-12.806	124.2870	22.2			
23/03/11	10:27	Sbruvs	Vul13		-12.803	124.2782	23.8			
23/03/11	10:31	Sbruvs	Vul14		-12.804	124.2716	25.4			
23/03/11	10:35	Sbruvs	Vul15		-12.802	124.2629	20.4			
23/03/11	10:39	Sbruvs	Vul16		-12.802	124.2561	34			
23/03/11	12:51	Sediment	Vul (East)	GA027	-12.809	124.3292				
23/03/11	13:05	Sbruvs	Vul17		-12.812	124.3072	33.1			
23/03/11	13:10	Sbruvs	Vul18		-12.810	124.2960	27			
23/03/11	13:14	Sbruvs	Vul19		-12.813	124.2945	24.9			
23/03/11	13:20	Sbruvs	Vul20		-12.809	124.2833	26			
23/03/11	13:23	Sbruvs	Vul21		-12.811	124.2779	26			
23/03/11	13:26	Sbruvs	Vul22		-12.809	124.2703	26.4			
23/03/11	13:30	Sbruvs	Vul23		-12.807	124.2633	22.6			
23/03/11	13:35	Sbruvs	Vul24		-12.798	124.2535	38.8			
23/03/11	O/N	Multibeam	Vul		-12.804	124.2815				
24/03/11	7:20	Sediment	She (North)	GA028	-12.502	124.1695				
24/03/11	7:40	Sediment	She (West)	GA029	-12.524	124.1551				
24/03/11	8:03	Sediment	She (South)	GA030	-12.523	124.1744				
24/03/11	8:18	Sediment	She (East)	GA031	-12.507	124.1879				
24/03/11	8:47	Sbruvs	She1		-12.509	124.1812	43.1			
24/03/11	8:50	Sbruvs	She2		-12.511	124.1786	35.8			
24/03/11	8:53	Sbruvs	She3		-12.509	124.1770	38.8			
24/03/11	8:56	Sbruvs	She4		-12.511	124.1746	34.8			
24/03/11	9:00	Sbruvs	She5		-12.512	124.1730	32.3			
24/03/11	9:05	Sbruvs	She6		-12.512	124.1706	31.8			
24/03/11	9:09	Sbruvs	She7		-12.514	124.1677	31.7			
24/03/11	9:11	Sbruvs	She8		-12.516	124.1664	32.9			
24/03/11	10:56	Sbruvs	She9		-12.513	124.1758	40.2			
24/03/11	10:59	Sbruvs	She10		-12.515	124.1734	37.5			
24/03/11	11:04	Sbruvs	She11		-12.515	124.1717	35.3			
24/03/11	11:06	Sbruvs	She12		-12.517	124.1713	34.1			
24/03/11	11:09	Sbruvs	She13		-12.514	124.1704	33.1			
24/03/11	11:13	Sbruvs	She14		-12.518	124.1687	31.4			
24/03/11	11:15	Sbruvs	She15		-12.517	124.1680	32.2			
24/03/11	11:19	Sbruvs	She16		-12.520	124.1662	37.6			
24/03/11	14:03	Towcam	She1		-12.515	124.1728	37.6	-12.510	124.1707	66.8
24/03/11	14:42	Towcam	She2		-12.513	124.1760	41.5	-12.508	124.1814	60.4

24/03/11	15:35	Towcam	She3		-12.518	124.1635	65.8	-12.511	124.1699	61.9
24/03/11	16:31	Towcam	She4		-12.523	124.1672	70.1	-12.518	124.1788	73.7
24/03/11	O/N	Multibeam	She		-12.515	124.1730				
24/03/11	O/N	Multibeam	Bar		-12.554	124.0196				
25/03/11	7:03	Sediment	Bae (North)	GA032	-12.530	124.0336				
25/03/11	7:18	Sediment	Bae (East)	GA033	-12.542	124.0605				
25/03/11	7:43	Towcam	She5		-12.514	124.1755	37.9	-12.522	124.1667	68.9
25/03/11	8:26	Towcam	She6		-12.516	124.1752	35.5	-12.517	124.1639	64.5
25/03/11	9:11	Towcam	She7		-12.514	124.1749	37.8	-12.509	124.1715	77.8
25/03/11	9:40	Towcam	She8		-12.514	124.1746	37.8	-12.519	124.1774	65.2
25/03/11	10:22	Towcam	She9		-12.516	124.1731	35.3	-12.515	124.1816	70.4
25/03/11	10:53	Towcam	She10		-12.518	124.1693	31.3	-12.513	124.1662	66.7
25/03/11	11:27	Towcam	She11		-12.519	124.1696	31.3	-12.522	124.1717	70.2
25/03/11	11:52	Towcam	She12		-12.515	124.1745	38.5	-12.520	124.1642	65.2
25/03/11	13:12	Sbruvs	She17		-12.520	124.1693	32.9			
25/03/11	13:14	Sbruvs	She18		-12.521	124.1717	35.5			
25/03/11	13:16	Sbruvs	She19		-12.519	124.1733	34.7			
25/03/11	13:21	Sbruvs	She20		-12.519	124.1755	38.3			
25/03/11	13:24	Sbruvs	She21		-12.518	124.1765	38.4			
25/03/11	13:27	Sbruvs	She22		-12.516	124.1776	37.6			
25/03/11	13:29	Sbruvs	She23		-12.515	124.1800	42			
25/03/11	13:31	Sbruvs	She24		-12.513	124.1810	44.3			
25/03/11	16:02	Towcam	She13		-12.508	124.1752	75	-12.513	124.1823	65
25/03/11	O/N	Multibeam	Bar		-12.554	124.0196				
26/03/11	7:49	Sbruvs	Bae1		-12.548	124.0474	33			
26/03/11	7:52	Sbruvs	Bae2		-12.545	124.0457	22.7			
26/03/11	7:56	Sbruvs	Bae3		-12.546	124.0421	20.4			
26/03/11	8:00	Sbruvs	Bae4		-12.550	124.0440	26.4			
26/03/11	8:03	Sbruvs	Bae5		-12.553	124.0419	36.5			
26/03/11	8:07	Sbruvs	Bae6		-12.549	124.0402	18.6			
26/03/11	8:11	Sbruvs	Bae7		-12.547	124.0348	19			
26/03/11	8:15	Sbruvs	Bae8		-12.545	124.0325	20.1			
26/03/11	10:17	Sbruvs	Bae9		-12.553	124.0305	24.8			
26/03/11	10:20	Sbruvs	Bae10		-12.552	124.0288	21.5			
26/03/11	10:24	Sbruvs	Bae11		-12.550	124.0304	19			
26/03/11	10:28	Sbruvs	Bae12		-12.548	124.0277	19.3			
26/03/11	10:31	Sbruvs	Bae13		-12.546	124.0278	20.5			
26/03/11	10:35	Sbruvs	Bae14		-12.547	124.0232	22.5			
26/03/11	10:39	Sbruvs	Bae15		-12.544	124.0224	22.8			
26/03/11	10:43	Sbruvs	Bae16		-12.548	124.0198	33.6			
26/03/11	13:32	Sbruvs	Bae17		-12.538	124.0474	42.2			
26/03/11	13:34	Sbruvs	Bae18		-12.538	124.0431	33.1			
26/03/11	13:38	Sbruvs	Bae19		-12.542	124.0410	24			
26/03/11	13:42	Sbruvs	Bae20		-12.538	124.0359	33			
26/03/11	13:46	Sbruvs	Bae21		-12.542	124.0316	22.7			
26/03/11	13:50	Sbruvs	Bae22		-12.539	124.0257	44.4			
26/03/11	13:54	Sbruvs	Bae23		-12.543	124.0253	21.6			
26/03/11	13:58	Sbruvs	Bae24		-12.543	124.0184	42.1			
26/03/11	15:30	Sediment	Bae (West)	GA034	-12.545	124.0084				
26/03/11	15:38	Sediment	Baw (West)	GA035	-12.563	123.9880				
26/03/11	16:16	Sediment	Baw (South)	GA036	-12.575	124.0069				
26/03/11	16:35	Sediment	Baw (East)	GA037	-12.560	124.0235				
26/03/11	16:54	Sediment	Bae (South)	GA038	-12.561	124.0348				
26/03/11	17:12	Sediment	Baw (North)	GA039	-12.571	123.5763				
26/03/11	O/N	Multibeam	Bar		-12.554	124.0196				
26/03/11	O/N	Multibeam	Wgb		-12.570	123.5979				
27/03/11	7:59	Sbruvs	Wgb1		-12.569	123.6053	49.7			
27/03/11	8:03	Sbruvs	Wgb2		-12.567	123.6027	48.1			
27/03/11	8:07	Sbruvs	Wgb3		-12.567	123.5964	43.5			

27/03/11	8:10	Sbruvs	Wgb4		-12.569	123.5918	48			
27/03/11	8:13	Sbruvs	Wgb5		-12.572	123.5919	46.3			
27/03/11	8:15	Sbruvs	Wgb6		-12.573	123.5938	46.6			
27/03/11	8:18	Sbruvs	Wgb7		-12.573	123.5962	41.8			
27/03/11	8:20	Sbruvs	Wgb8		-12.573	123.5986	46.3			
27/03/11	10:32	Sbruvs	Wgb9		-12.569	123.5983	41.1			
27/03/11	10:35	Sbruvs	Wgb10		-12.570	123.5941	40			
27/03/11	10:38	Sbruvs	Wgb11		-12.570	123.5963	38.4			
27/03/11	10:41	Sbruvs	Wgb12		-12.571	123.5994	40.9			
27/03/11	10:43	Sbruvs	Wgb13		-12.572	123.6011	46.8			
27/03/11	10:46	Sbruvs	Wgb14		-12.571	123.6031	46.1			
27/03/11	10:48	Sbruvs	Wgb15		-12.569	123.6029	44.4			
27/03/11	10:50	Sbruvs	Wgb16		-12.567	123.6005	45.2			
27/03/11	13:51	Towcam	Wgb1		-12.570	123.5973	40.9	-12.568	123.5921	63.7
27/03/11	14:19	Towcam	Wgb2		-12.570	123.5982	41.9	-12.571	123.5907	61.6
27/03/11	15:00	Towcam	Wgb3		-12.570	123.5980	41.9	-12.574	123.5955	75.6
27/03/11	15:31	Towcam	Wgb4		-12.569	123.5978	42	-12.573	123.5937	67.8
27/03/11	16:06	Towcam	Wgb5		-12.570	123.5976	41.5	-12.573	123.6016	65.8
27/03/11	16:39	Towcam	Wgb6		-12.567	123.6000	50.4	-12.572	123.6040	62.9
27/03/11	17:23	Towcam	Wgb7		-12.566	123.6029	54.2	-12.567	123.6102	62.9
27/03/11	O/N	Multibeam	Shoal33		-12.595	124.3756				
28/03/11	7:54	Sbruvs	Baw1		-12.561	124.0175	47			
28/03/11	7:57	Sbruvs	Baw2		-12.557	124.0154	40.9			
28/03/11	7:59	Sbruvs	Baw3		-12.555	124.0132	40.1			
28/03/11	8:02	Sbruvs	Baw4		-12.555	124.0093	31.4			
28/03/11	8:05	Sbruvs	Baw5		-12.555	124.0061	32.7			
28/03/11	8:07	Sbruvs	Baw6		-12.557	124.0024	29.4			
28/03/11	8:11	Sbruvs	Baw7		-12.559	123.9989	32.1			
28/03/11	8:13	Sbruvs	Baw8		-12.560	123.9967	38.6			
28/03/11	10:12	Sbruvs	Baw9		-12.563	123.9980	33.4			
28/03/11	10:14	Sbruvs	Baw10		-12.566	123.9998	33.5			
28/03/11	10:17	Sbruvs	Baw11		-12.565	124.0026	26.3			
28/03/11	10:20	Sbruvs	Baw12		-12.568	124.0041	37			
28/03/11	10:23	Sbruvs	Baw13		-12.565	124.0057	26.7			
28/03/11	10:26	Sbruvs	Baw14		-12.568	124.0100	37.5			
28/03/11	10:29	Sbruvs	Baw15		-12.564	124.0107	30.2			
28/03/11	10:33	Sbruvs	Baw16		-12.565	124.0156	39.4			
28/03/11	13:11	Sbruvs	Baw17		-12.562	124.0121	33			
28/03/11	13:14	Sbruvs	Baw18		-12.559	124.0109	32.9			
28/03/11	13:18	Sbruvs	Baw19		-12.558	124.0072	30.9			
28/03/11	13:20	Sbruvs	Baw20		-12.560	124.0085	32.5			
28/03/11	13:23	Sbruvs	Baw21		-12.562	124.0072	31.4			
28/03/11	13:26	Sbruvs	Baw22		-12.562	124.0042	28.6			
28/03/11	13:28	Sbruvs	Baw23		-12.560	124.0037	31.2			
28/03/11	13:32	Sbruvs	Baw24		-12.561	124.0013	27.1			
28/03/11	15:23	Towcam	Baw1		-12.560	124.0066	32.3	-12.557	124.0155	64.9
28/03/11	16:02	Towcam	Baw2		-12.564	124.0090	31.2	-12.562	123.9955	67.4
28/03/11	16:53	Towcam	Baw3		-12.566	124.0005	34.8	-12.554	124.0107	69.1
28/03/11	19:01	Towcam	San1		-12.462	123.7796	35.3	-12.453	123.7729	36.9
28/03/11	O/N	Multibeam	Sandwaves		-12.465	123.7802				
29/03/11	8:06	Towcam	Baw4		-12.565	124.0110	30.6	-12.565	124.0163	65.1
29/03/11	8:39	Towcam	Baw5		-12.562	124.0022	26.5	-12.557	123.9989	77.9
29/03/11	9:07	Towcam	Baw6		-12.561	124.0040	29.3	-12.555	124.0039	70
29/03/11	9:53	Towcam	Baw7		-12.561	124.0052	31.9	-12.562	124.0180	65.4
29/03/11	10:41	Towcam	Baw8		-12.557	124.0009	32.2	-12.558	124.0096	31.9
29/03/11	11:22	Towcam	Baw9		-12.564	123.9964	43.1	-12.567	124.0144	67.1
29/03/11	13:15	Towcam	Bae1		-12.545	124.0327	20.7	-12.538	124.0484	71.1
29/03/11	14:12	Towcam	Bae2		-12.545	124.0330	20.7	-12.551	124.0202	73
29/03/11	15:02	Towcam	Bae3		-12.550	124.0378	19	-12.545	124.0505	70.2

29/03/11	15:46	Towcam	Bae4		-12.550	124.0395	19.8	-12.555	124.0288	64.5
29/03/11	16:29	Towcam	Bae5		-12.542	124.0282	20.2	-12.536	124.0400	63.8
29/03/11	17:18	Towcam	Bae6		-12.541	124.0285	20.8	-12.545	124.0160	65.2
29/03/11	18:04	Sediment	Bae (Shallow)	GA041	-12.537	124.0366				
29/03/11	18:19	Sediment	Bae (Shallow)	GA042	-12.537	124.0368				
29/03/11	O/N	Multibeam	She		-12.515	124.1730				
29/03/11	O/N	Multibeam	Bar		-12.554	124.0196				
30/03/11	8:34	Towcam	Eug20		-13.073	124.5787	19.4	-13.079	124.5963	62.8
30/03/11	9:38	Towcam	Eug21		-13.074	124.5821	23.8	-13.072	124.5951	62.6
30/03/11	10:22	Towcam	Eug22		-13.071	124.5899	36.8	-13.066	124.5814	63.8
30/03/11	11:12	Towcam	Eug23		-13.073	124.5818	22.6	-13.077	124.5669	63.1
30/03/11	12:10	Towcam	Eug24		-13.072	124.5729	23.4	-13.071	124.5654	54.7
30/03/11	13:27	Towcam	Eug25		-13.078	124.5802	19.7	-13.083	124.5761	68.2
30/03/11	13:57	Towcam	Eug26		-13.083	124.5832	23.4	-13.087	124.5911	50.1
30/03/11	14:34	Towcam	Eug27		-13.087	124.5919	47.7	-13.078	124.5911	30
30/03/11	O/N	Multibeam	Eug		-13.075	124.5799				
31/03/11	O/N	Multibeam	Hey		-13.450	124.0450				
4/04/11	11:01	Sediment	Sampson Inlet Inner	GA051	-15.495	124.4834				
4/04/11	11:28	Sediment	Sampson Inlet Mouth	GA052	-15.509	124.4640				
5/04/11	6:42	Sediment	Ech (North)	GA043	-13.879	123.9264				
5/04/11	7:10	Sediment	Ech (West)	GA044	-13.900	123.8720				
5/04/11	7:46	Sediment	Ech (South)	GA045	-13.939	123.9249				
5/04/11	8:56	Sediment	Ech (East)	GA046	-13.913	123.9644				
5/04/11	8:36	Sbruvs	Ech1		-13.916	123.9175	21.3			
5/04/11	8:39	Sbruvs	Ech2		-13.911	123.9150	22.6			
5/04/11	8:44	Sbruvs	Ech3		-13.911	123.9235	24.5			
5/04/11	8:48	Sbruvs	Ech4		-13.908	123.9198	24.2			
5/04/11	8:52	Sbruvs	Ech5		-13.906	123.9241	28.5			
5/04/11	8:55	Sbruvs	Ech6		-13.902	123.9242	37.5			
5/04/11	8:59	Sbruvs	Ech7		-13.898	123.9203	36.1			
5/04/11	9:02	Sbruvs	Ech8		-13.901	123.9164	26.4			
5/04/11	10:51	Sbruvs	Ech9		-13.905	123.9162	25.1			
5/04/11	10:54	Sbruvs	Ech10		-13.903	123.9104	24.5			
5/04/11	10:57	Sbruvs	Ech11		-13.898	123.9108	25.7			
5/04/11	11:03	Sbruvs	Ech12		-13.898	123.9021	23.4			
5/04/11	11:06	Sbruvs	Ech13		-13.893	123.9030	31.5			
5/04/11	11:10	Sbruvs	Ech14		-13.894	123.8966	23.3			
5/04/11	11:13	Sbruvs	Ech15		-13.891	123.8970	40.4			
5/04/11	11:18	Sbruvs	Ech16		-13.896	123.8909	20.8			
5/04/11	13:46	Sbruvs	Ech17		-13.899	123.8941	19.2			
5/04/11	13:50	Sbruvs	Ech18		-13.902	123.8929	21.8			
5/04/11	13:53	Sbruvs	Ech19		-13.905	123.8909	33			
5/04/11	13:58	Sbruvs	Ech20		-13.908	123.8955	25			
5/04/11	14:02	Sbruvs	Ech21		-13.910	123.8994	24.1			
5/04/11	14:07	Sbruvs	Ech22		-13.907	123.9060	22.5			
5/04/11	14:10	Sbruvs	Ech23		-13.904	123.9042	23.3			
5/04/11	14:13	Sbruvs	Ech24		-13.902	123.8991	22.5			
5/04/11	16:41	Towcam	ECH1		-13.897	123.8966	18.1	-13.891	123.8870	61.3
5/04/11	17:21	Towcam	ECH2		-13.895	123.8943	18	-13.902	123.9055	21.3
5/04/11	O/N	Multibeam	Ech		-13.903	123.9068				
6/04/11	6:12	Sediment	Hey (West)	GA047	-13.439	123.9859				
6/04/11	6:45	Sediment	Hey (North)	GA048	-13.404	124.0434				
6/04/11	7:20	Towcam	Ech3		-13.911	123.9163	20.3	-13.916	123.9026	64
6/04/11	8:09	Towcam	Ech4		-13.911	123.9151	21.3	-13.906	123.9303	62.4
6/04/11	9:06	Towcam	Ech5		-13.902	123.9063	23.3	-13.911	123.8926	62
6/04/11	9:58	Towcam	Ech6		-13.904	123.9038	23.1	-13.896	123.9189	62.1
6/04/11	10:55	Towcam	Ech7		-13.895	123.9004	23.6	-13.897	123.8848	62.2
6/04/11	13:06	Towcam	Ech8		-13.902	123.9048	25.3	-13.908	123.9144	23.6

6/04/11	13:57	Towcam	Ech9		-13.908	123.9154	23.8	-13.913	123.9229	23.9
6/04/11	14:39	Towcam	Ech10		-13.913	123.9234	23.6	-13.919	123.9325	62.9
6/04/11	15:42	Towcam	Ech11		-13.910	123.9173	22.2	-13.920	123.9107	68.9
6/04/11	16:25	Towcam	Ech12		-13.903	123.8935	19.3	-13.889	123.8939	66.2
6/04/11	17:10	Sediment	Hey (South)	GA049	-13.487	124.0325				
6/04/11	17:17	Towcam	Ech13		-13.903	123.8931	19.1	-13.912	123.8932	65.8
6/04/11	17:36	Sediment	Hey (East)	GA050	-13.444	124.0878				
6/04/11	17:52	Towcam	Ech14		-13.895	123.9004	19.6	-13.893	123.9135	63
6/04/11	19:09	Towcam	Ech15		-13.911	123.9177	20.3	-13.900	123.9251	63
6/04/11	19:55	Towcam	Ech16		-13.913	123.9191	20.8	-13.922	123.9250	62.1
6/04/11	O/N	Multibeam	Ech		-13.903	123.9068				
7/04/11	7:31	Sbruvs	Hey1		-13.418	124.0184	43.2			
7/04/11	7:36	Sbruvs	Hey2		-13.425	124.0118	27.8			
7/04/11	7:43	Sbruvs	Hey3		-13.428	124.0077	32.5			
7/04/11	7:47	Sbruvs	Hey4		-13.437	124.0103	37.9			
7/04/11	7:51	Sbruvs	Hey5		-13.433	124.0139	25.8			
7/04/11	7:53	Sbruvs	Hey6		-13.428	124.0157	18.3			
7/04/11	7:58	Sbruvs	Hey7		-13.427	124.0229	22.7			
7/04/11	8:00	Sbruvs	Hey8		-13.424	124.0253	30.8			
7/04/11	9:45	Sbruvs	Hey9		-13.426	124.0342	42.6			
7/04/11	9:49	Sbruvs	Hey10		-13.431	124.0398	35.4			
7/04/11	9:51	Sbruvs	Hey11		-13.434	124.0371	28.7			
7/04/11	9:55	Sbruvs	Hey12		-13.433	124.0309	24.4			
7/04/11	9:58	Sbruvs	Hey13		-13.434	124.0255	24.3			
7/04/11	10:01	Sbruvs	Hey14		-13.439	124.0238	22.1			
7/04/11	10:05	Sbruvs	Hey15		-13.441	124.0181	29.5			
7/04/11	10:12	Sbruvs	Hey16		-13.441	124.0126	49.6			
7/04/11	12:06	Sbruvs	Hey17		-13.432	124.0455	44.1			
7/04/11	12:10	Sbruvs	Hey18		-13.437	124.0508	41.4			
7/04/11	12:14	Sbruvs	Hey19		-13.443	124.0573	41.1			
7/04/11	12:19	Sbruvs	Hey20		-13.444	124.0479	28.7			
7/04/11	12:23	Sbruvs	Hey21		-13.448	124.0425	27.2			
7/04/11	12:27	Sbruvs	Hey22		-13.442	124.0389	26.8			
7/04/11	12:32	Sbruvs	Hey23		-13.442	124.0278	24.7			
7/04/11	12:37	Sbruvs	Hey24		-13.446	124.0171	43.6			
7/04/11	14:43	Sbruvs	Hey25		-13.449	124.0273	27.4			
7/04/11	14:47	Sbruvs	Hey26		-13.446	124.0311	23.2			
7/04/11	14:54	Sbruvs	Hey27		-13.451	124.0392	25.5			
7/04/11	14:57	Sbruvs	Hey28		-13.453	124.0447	24.8			
7/04/11	15:02	Sbruvs	Hey29		-13.458	124.0410	22.9			
7/04/11	15:06	Sbruvs	Hey30		-13.460	124.0340	33.9			
7/04/11	15:10	Sbruvs	Hey31		-13.457	124.0310	29.9			
7/04/11	15:14	Sbruvs	Hey32		-13.455	124.0269	36.1			
7/04/11	O/N	Multibeam	Hey		-13.450	124.0450				
8/04/11	8:03	Towcam	Hey1		-13.428	124.0204	19.8	-13.419	124.0092	66.7
8/04/11	8:51	Towcam	Hey2		-13.429	124.0205	20	-13.437	124.0310	25.2
8/04/11	9:26	Towcam	Hey3		-13.438	124.0312	25.4	-13.446	124.0426	25.1
8/04/11	10:14	Towcam	Hey4		-13.446	124.0410	25.6	-13.449	124.0462	25.8
8/04/11	10:49	Towcam	Hey4B		-13.451	124.0484	26	-13.453	124.0509	21.4
8/04/11	11:12	Towcam	Hey5		-13.449	124.0444	26.6	-13.437	124.0546	49.5
8/04/11	12:03	Towcam	Hey6		-13.442	124.0337	25.7	-13.438	124.0468	33.8
8/04/11	13:12	Towcam	Hey7		-13.442	124.0348	27	-13.447	124.0223	31.1
8/04/11	14:36	Towcam	Hey8		-13.435	124.0255	25.2	-13.447	124.0171	65.3
8/04/11	15:30	Towcam	Hey9		-13.434	124.0256	23.9	-13.424	124.0339	55.6
8/04/11	16:14	Towcam	Hey10		-13.429	124.0175	2.8	-13.418	124.0186	73.6
8/04/11	16:51	Towcam	Hey11		-13.427	124.0176	18.9	-13.438	124.0196	17.3
8/04/11	17:29	Towcam	Hey12		-13.446	124.0312	21.4	-13.447	124.0312	19.4
8/04/11	O/N	Multibeam	Hey		-13.450	124.0450				
9/04/11	7:23	Towcam	Goe13		-12.890	124.3466	41.9	-12.881	124.3538	74.1

9/04/11	8:03	Towcam	Goe14		-12.888	124.3409	30.7	-12.880	124.3410	31.9
9/04/11	8:42	Panda	Goe1		-12.884	124.3410	28.1	-12.887	124.3405	29.1
9/04/11	8:59	Panda	Goe2		-12.882	124.3419	32.4	-12.885	124.3418	30.7
9/04/11	9:20	Panda	Goe3		-12.888	124.3472	32.4	-12.890	124.3468	66
9/04/11	9:31	Sediment	Goe (South)	GA053	-12.884	124.3319				
9/04/11	9:56	Sediment	Goe (North)	GA054	-12.881	124.3310				
9/04/11	10:36	Towcam	Vul1		-12.801	124.2652	17.3	-12.804	124.2552	65.2
9/04/11	11:24	Towcam	Vul2		-12.804	124.2545	62.8	-12.793	124.2637	68.5
9/04/11	12:22	Panda	Vul1		-12.799	124.2578	28.6	-12.799	124.2580	28
9/04/11	13:01	Towcam	Vul3		-12.800	124.2676	20.1	-12.797	124.2521	65.9
9/04/11	14:04	Towcam	Vul4		-12.800	124.2678	20.5	-12.803	124.2780	24.7
9/04/11	14:38	Towcam	Vul5		-12.802	124.2761	25.4	-12.805	124.2878	22.7
9/04/11	15:17	Towcam	Vul6		-12.804	124.2844	24.1	-12.807	124.2991	23.7
9/04/11	16:08	Towcam	Vul7		-12.808	124.3017	23	-12.812	124.2943	23
9/04/11	16:39	Towcam	Vul8		-12.812	124.2937	23.3	-12.816	124.2844	64.7
9/04/11	17:21	Towcam	Vul9		-12.804	124.2701	20.1	-12.814	124.2763	69.2
9/04/11	O/N	Multibeam	Hey		-13.450	124.0450				
10/04/11	6:07	Towcam	Vul10		-12.797	124.2754	24.1	-12.801	124.2655	15.5
10/04/11	7:27	Towcam	Vul11		-12.797	124.2750	23.9	-12.794	124.2861	64.1
10/04/11	8:12	Towcam	Vul12		-12.804	124.2700	19.3	-12.793	124.2634	66.7
10/04/11	9:00	Towcam	Vul13		-12.801	124.2662	16.1	-12.792	124.2694	67.8
10/04/11	9:33	Towcam	Vul14		-12.801	124.2662	2.2	-12.809	124.2635	67.1
10/04/11	10:08	Towcam	Vul15		-12.804	124.2849	21.9	-12.794	124.2881	66
10/04/11	10:45	Towcam	Vul16		-12.804	124.2851	22.5	-12.816	124.2820	67
10/04/11	11:25	Panda	Vul2		-12.799	124.2867	22.8	-12.798	124.2865	25.4
10/04/11	12:57	Towcam	Vul17		-12.807	124.2993	23	-12.810	124.3117	77.1
10/04/11	13:37	Towcam	Vul18		-12.808	124.3008	23	-12.804	124.3106	75.4
10/04/11	14:13	Towcam	Vul19		-12.805	124.3039	21.7	-12.796	124.2987	66.3
10/04/11	14:47	Towcam	Vul20		-12.805	124.3041	21.4	-12.814	124.3088	66.2
10/04/11	15:19	Towcam	Vul21		-12.806	124.3064	24.8	-12.800	124.3079	65.8
10/04/11	15:42	Towcam	Vul22		-12.805	124.3068	25.5	-12.816	124.3040	78.7
10/04/11	16:24	Sediment	Vul (Shallow)	GA055	-12.800	124.3007				
10/04/11	19:03	Towcam	33-1		-12.607	124.3743	53.3	-12.594	124.3790	61.6
10/04/11	20:04	Towcam	33-2S		-12.597	124.3254	60.9			
10/04/11	O/N	Multibeam	Shoal33		-12.595	124.3756				
11/04/11	7:30	Sbruvs	Bae25		-12.536	124.0352	81.3			
11/04/11	7:37	Sbruvs	Bae26		-12.537	124.0471	75.9			
11/04/11	7:42	Sbruvs	Bae27		-12.543	124.0507	74.4			
11/04/11	7:46	Sbruvs	Bae28		-12.551	124.0472	76.7			
11/04/11	7:51	Sbruvs	Bae29		-12.555	124.0374	74.3			
11/04/11	7:57	Sbruvs	Bae30		-12.553	124.0239	76			
11/04/11	8:02	Sbruvs	Bae31		-12.545	124.0155	77.9			
11/04/11	8:06	Sbruvs	Bae32		-12.539	124.0227	73.9			
11/04/11	9:49	Towcam	Bae7		-12.547	124.0297	19.3	-12.554	124.0399	68.5
11/04/11	10:26	Towcam	Bae8		-12.547	124.0290	19.5	-12.540	124.0205	67.9
11/04/11	11:01	Towcam	Bae9		-12.542	124.0186	42.4	-12.550	124.0186	69.9
11/04/11	11:29	Towcam	Bae10		-12.543	124.0249	19.8	-12.554	124.0250	71.8
11/04/11	12:05	Towcam	Bae11		-12.554	124.0301	36.5	-12.546	124.0300	19.2
11/04/11	13:14	Towcam	Bae12		-12.544	124.0383	22.6	-12.552	124.0442	69.8
11/04/11	13:47	Towcam	Bae13		-12.545	124.0387	21.6	-12.536	124.0331	63.9
11/04/11	14:22	Towcam	Bae14		-12.546	124.0300	19.7	-12.537	124.0300	77.1
11/04/11	14:53	Towcam	Bae15		-12.536	124.0429	41.5	-12.545	124.0503	64.8
11/04/11	15:33	Towcam	Bae16		-12.545	124.0402	21	-12.541	124.0488	38.6
11/04/11	16:07	Towcam	Bae17		-12.538	124.0478	44.5	-12.538	124.0272	63
11/04/11	16:56	Towcam	Bae18		-12.543	124.0327	22.2	-12.551	124.0397	20.2
11/04/11	O/N	Multibeam	Shoal33		-12.595	124.3756				
12/04/11	7:22	Sbruvs	Hey33		-13.449	124.0511	23.9			
12/04/11	7:25	Sbruvs	Hey34		-13.452	124.0551	25.6			
12/04/11	7:32	Sbruvs	Hey35		-13.459	124.0535	20.9			

12/04/11	7:36	Sbruvs	Hey36		-13.463	124.0483	21.4			
12/04/11	7:41	Sbruvs	Hey37		-13.467	124.0502	23.2			
12/04/11	7:44	Sbruvs	Hey38		-13.470	124.0466	30.7			
12/04/11	7:48	Sbruvs	Hey39		-13.466	124.0404	33.4			
12/04/11	7:51	Sbruvs	Hey40		-13.462	124.0402	26.4			
12/04/11	9:37	Sbruvs	Hey41		-13.473	124.0495	33			
12/04/11	9:41	Sbruvs	Hey42		-13.473	124.0574	27.5			
12/04/11	9:44	Sbruvs	Hey43		-13.468	124.0596	21.4			
12/04/11	9:48	Sbruvs	Hey44		-13.462	124.0582	22.2			
12/04/11	9:50	Sbruvs	Hey45		-13.459	124.0573	22.8			
12/04/11	9:54	Sbruvs	Hey46		-13.459	124.0629	29.5			
12/04/11	9:58	Sbruvs	Hey47		-13.453	124.0638	36.9			
12/04/11	10:01	Sbruvs	Hey48		-13.449	124.0613	36.8			
12/04/11	11:44	Sbruvs	Hey49		-13.448	124.0671	49.4			
12/04/11	11:48	Sbruvs	Hey50		-13.456	124.0720	49.8			
12/04/11	11:52	Sbruvs	Hey51		-13.464	124.0708	42.2			
12/04/11	11:54	Sbruvs	Hey52		-13.467	124.0681	31.8			
12/04/11	11:58	Sbruvs	Hey53		-13.474	124.0639	33.7			
12/04/11	12:03	Sbruvs	Hey54		-13.480	124.0689	46.1			
12/04/11	12:07	Sbruvs	Hey55		-13.477	124.0719	43.5			
12/04/11	12:10	Sbruvs	Hey56		-13.472	124.0753	46.1			
12/04/11	14:00	Sbruvs	Hey57		-13.469	124.0879	49			
12/04/11	14:05	Sbruvs	Hey58		-13.469	124.0793	47.6			
12/04/11	14:09	Sbruvs	Hey59		-13.473	124.0824	42.6			
12/04/11	14:12	Sbruvs	Hey60		-13.476	124.0860	44.5			
12/04/11	14:15	Sbruvs	Hey61		-13.476	124.0906	47.5			
12/04/11	14:19	Sbruvs	Hey62		-13.482	124.0861	44.2			
12/04/11	14:23	Sbruvs	Hey63		-13.481	124.0799	41.3			
12/04/11	14:25	Sbruvs	Hey64		-13.482	124.0757	42.4			
12/04/11	21:13	Towcam	Vul23		-12.802	124.2765	23.8	-12.801	124.2864	22.1
12/04/11	21:47	Towcam	Vul24		-12.806	124.2981	21.9	-12.806	124.3084	28.9
12/04/11	22:43	Sediment	Vul (Shallow)	GA056	-12.802	124.2788				
13/04/11	7:32	Towcam	Hey13		-13.453	124.0510	23.9	-13.464	124.0646	26.9
13/04/11	8:22	Towcam	Hey14		-13.464	124.0650	27.9	-13.477	124.0807	41.8
13/04/11	9:19	Towcam	Hey15		-13.477	124.0806	41.3	-13.484	124.0896	65
13/04/11	10:01	Towcam	Hey16		-13.485	124.0823	41.2	-13.462	124.0816	50.9
13/04/11	11:14	Towcam	Hey17		-13.469	124.1016	82.5	-13.482	124.0700	61.6
13/04/11	13:31	Towcam	Hey18		-13.438	124.0643	68.7	-13.462	124.0608	22.5
13/04/11	14:31	Towcam	Hey19		-13.462	124.0602	21.4	-13.479	124.0572	63.5
13/04/11	15:22	Towcam	Hey20		-13.466	124.0394	36.2	-13.465	124.0517	21.1
13/04/11	O/N	Multibeam	Hey		-13.450	124.0450				
14/04/11	7:35	Sediment	Cornea Seep	GA057	-13.655	124.7117				
14/04/11	7:43	Sediment	Cornea Seep	GA058	-13.653	124.7116				
14/04/11	8:39	Sediment	Cornea Seep	GA059	-13.510	124.7083				
14/04/11	9:48	Sediment	Cornea Seep	GA060	-13.413	124.7008				
14/03/11	O/N	Multibeam	Hey		-13.450	124.0450				
14/04/11	O/N	Multibeam	Ech		-13.903	123.9068				