Montara: 2011 Shallow Reef Surveys at Ashmore, Cartier and Seringapatam Reefs

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Cover photo – Cartier Reef, location C6 m March 2011.(AIMS)

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EXECUTIVE SUMMARY

Background

In response to the triggering of the Coral Reefs (S6) component of the PTTEP Australasia (Ashmore Cartier) Pty Ltd (PTTEPAA)/Dept. of SEWPaC Monitoring Plan for the Montara Well Release Timor Sea, PTTEP commissioned the Australian Institute of Marine Science (AIMS) to conduct surveys of shallow reef benthic habitats in the vicinity of the Montara well head platform in April 2010. Ashmore Reef and Cartier Islet were the principal emergent reefs of interest, as they were closest to the Montara Well Head platform. To provide a control location, the same sampling was conducted at Seringapatam Reef, a similar emergent reef in the same bioregion, but several hundred kilometres to the south-west and well away from modelled spill trajectories.

The condition of the benthic communities at Ashmore and Cartier Reefs in the previous survey in 2010 was consistent with surveys conducted before the uncontrolled release. Although there was no evidence of recent major disturbance that could be attributable to any uncontrolled release, there was evidence of a recent coral bleaching event that was most likely caused by elevated water temperatures (Heyward et al. 2010). Notwithstanding the lack of a major impact, more subtle potential effects from hydrocarbons could not be ruled out and there remained knowledge gaps regarding coral reproduction and the recovery or otherwise of the bleached corals. Consequently, a follow up survey was commissioned by PTTEPAA in 2011 (Coral Reefs S6B), and the results of the surveys are presented here.

The most recent 2011 survey enabled a repeated assessment of the shallow reef benthos to ascertain the ongoing state of the coral communities. In addition, an extended and more diverse selection of sampling was undertaken to see if processes of ongoing coral population renewal via sexual reproduction and recruitment were occurring. The 2011 surveys were broader in scope than the 2010 assessment, including comprehensive assessment of the fish communities associated with the benthic sites, as well as a re-sampling of reef sediments to follow up on the status of hydrocarbon detections noted in the 2010 report.

Reef benthic community status in 2011

The 2011 repeat survey of shallow reefs was undertaken using the reef edge locations established in 2010, allowing a direct comparison of changes within and between reefs. Overall composition of the shallow reef benthos at Ashmore, Cartier and Seringapatam Reefs has remained consistent between 2010 and 2011, with live hard coral and turf algae being the dominant groups. Average live coral cover is increasing at all reefs, at a similar modest rate, although with some variability between locations within each reef. The mean positive change in hard coral abundance at reef level, of 2.6%, is a medium rate of change compared to reports from other reefs.

At the whole reef scale, the benthic community structure and patterns of temporal change from 2010-11 were very similar between the three reefs. There is no evidence of broadscale disturbance that correlates with the presence of an uncontrolled release closer to Ashmore and Cartier reefs than to Seringapatam.

The coral bleaching observed in 2010 was largely absent in 2011, with only residual occurrences associated with individual coral colonies. The two coral families most affected by bleaching in 2010, Acroporidae and Pocilloporidae, showed a significant reduction in their bleached status, with most

colonies now displaying normal pigmentation. The presence of numerous adult sized colonies of species that were originally widely bleached suggests that many corals observed as bleached in 2010 have survived and recovered. At Seringapatam, where Pocilloporid species were most strongly affected by the 2010 bleaching, changes at each of the six monitoring locations showed a majority had experienced a decline in the abundance of this family. However, there was no clear correlation between the level of bleaching measured in this family at each location in 2010 and the amount of coral loss recorded in 2011. Overall, it would seem likely that the duration and intensity of bleaching stress at Seringapatam in 2010 was greater than experienced at Ashmore or Cartier Reefs, with subsequently greater loss of the more sensitive species at Seringapatam.

The rates of change in live coral are slower than would have been predicted from the most recent previous studies, but in keeping with older reports from other undisturbed reefs in the region. Unless these reefs face further disturbance, through cyclones, bleaching or pollution, the current monitoring design should confirm significant coral growth continuing in the next few years.

Coral reproduction

The analysis of more than fifty coral species for gonad condition provides valuable new insights into coral reproduction in the Ashmore Reef and Cartier Islet marine reserves. High participation rates in normal gametogenesis typical of broadcast spawning species is taking place, with developing or mature gonads found in all but a few species.

The high levels of gametogenic activity seen in most species during the autumn and spring spawning periods confirms that reproduction is occurring on Ashmore, Cartier and Seringapatam Reefs following the 2009 Montara uncontrolled release. There are significant differences in gamete condition within and between reefs for many species, but there is no clear pattern that points to a consistent difference between the two reefs closest to the uncontrolled release and the far removed control reef.

The timing of coral broadcast spawning at these reefs is yet to be comprehensively observed, but inference from the gonad condition indices point to likely broadcast spawning periods following full moons in mid-late September and February-March. Multiple species appear to spawn during the same months, but the peak month of multi-specific spawning has not yet been determined.

A number of brooding species can be common and important components of the coral community. These include *Acropora palifera, Pocillopora damicornis, Pocillopora verrucosa, Seriatopora hystrix* and *Stylophora pistillata*. Histological examination of these species revealed gametes in most developmental stages.

There is evidence of both synchrony within species and asynchrony between species within and between reefs, with some corals only spawning in the spring, some in the autumn and some species may spawn in both seasons.

The composition and mean number of coral recruits settling on the reef is very similar between Ashmore, Cartier and Seringapatam Reefs, providing no evidence that recruitment is abnormally low at Ashmore and Cartier following the Montara uncontrolled release. The overall levels of recruits per tile at these three reefs are low in comparison to some other studies, such as on the Great Barrier Reef, but in the same range as recorded for other Indian Ocean Reefs.

The patterns of juvenile coral abundance were found to be very similar between Ashmore, Cartier and Seringapatam Reefs, as was the case for newly settling coral recruits. These data suggest that very similar processes of recruitment and post-settlement survival are operating at these reefs. The

numbers of recruits are comparable with reefs supporting similar levels of spawning coral stock on the Great Barrier Reef. Overall, the patterns look normal and the two reefs closest to the Montara uncontrolled release (Ashmore and Cartier) do not show anything unusual in relation to juvenile coral abundance.

A major difference in coral recruitment and juvenile abundance was noted between the three principal study reefs and Scott Reef. We hypothesise that this may relate to a longer period for spawning stock recovery since disturbance at Scott Reef, the availability of significant sheltered lagoon areas and its local scale hydrodynamics promoting high levels of larval retenion.

Reef fish community status in 2011

The aim of this study was to determine if there were any patterns in the size, abundance and composition of fish communities on reefs consistent with affects from the Montara uncontrolled release..

Using underwater visual census (UVC) and diver operated stereo video (DOV) techniques along the same transects used for the benthic study, we recorded the densities, biomass and lengths of reef fishes at Ashmore, Cartier and Seringapatam Reefs in March 2011. The survey recorded a total of 116,110 individuals from 309 species and 29 families. The UVC method recorded a total of 70,280 fishes from 258 species, while DOVs recorded 45,830 fishes from 199 species.

Multivariate analyses of species composition data showed that the structure of fish assemblages at Seringapatam Reef, was significantly different from those of both Ashmore and Cartier Reefs. The difference was mainly attributable to lower densities of the damselfishes *Chromis margaritifer*, *Chrysiptera rex* and *Plectroglyphidodon dickii* and higher densities of *Pomacentrus lepidogenys* and *Pomacentrus coelestis* at Ashmore and Cartier compared to Seringapatam Reefs.

Greater abundances of *P. coelestis* at Ashmore and particularly Cartier Reef are noteworthy because this species is known to recruit preferentially to degraded reef habitats (dead coral and rubble). While the possibility that this is an impact from the uncontrolled release cannot be eliminated, these higher densities of *P. coelestis* could also be the result of disturbance events such as cyclones and coral bleaching that reduce cover of live coral. The relative influence of these different impacts cannot be determined without data on the benthic habitats prior to the uncontrolled release.

Fish communities displayed evidence that other disturbances had affected community structure. Ashmore, Cartier and Seringapatam Reefs had higher proportions of herbivorous fishes, particularly surgeonfishes, than other studies have reported for the more distant Rowley Shoals. Herbivores such as these typically increase in response to loss of live coral and its replacement by turfing algae, thus higher abundances of herbivores on our study reefs probably reflect a history of disturbance prior to the oil uncontrolled release.

We found no obvious patterns in species richness, biomass, density and size structure of fish assemblages that were consistent with the effects of the Montara uncontrolled release. There appeared to be no impacts of the uncontrolled release on the recruitment of reef fishes, since we found no evidence of missing or truncated size classes in size-frequency distributions.

Sediment Hydrocarbon Analysis

Studies of hydrocarbon concentrations in sediments at Ashmore, Cartier and Seringapatam Reefs in 2010 (conducted five months after the discharge of oil and gas from the Montara well ceased) showed concentrations above detection limits in ~49% of samples, generally low hydrocarbon levels,

and a pattern of greater hydrocarbon levels at Ashmore and Cartier reefs (see S6 Coral Reefs, Heyward et al. 2010). In the present survey (S6B Coral Reefs), conducted ~fifteen months after the discharge ceased, hydrocarbons recorded in fewer samples (35%), the petroleum hydrocarbon levels were lower, but there was still a pattern of greater hydrocarbon concentrations at Ashmore Reef.

The GCMS analyses (Table 5.3) and reconstructed ion chromatogram analyses showed the hydrocarbons had patterns typical of degraded oil, including a bimodal distribution (as also seen in the 2010 study). In 2011, the sediments had high concentrations of diploptene (the biomarker for sulfate reducing bacteria that are known to degrade hydrocarbons) and the sterane and triterpane biomarkers expected for a degraded crude oil. Collectively these results are consistent with weathering processes which have changed concentrations and chromatogram patterns.

Oil was observed at Ashmore Reef during the uncontrolled release, and given the higher presence of hydrocarbons there (as compared with the more distantly located Seringapatam Reef), the pattern is consistent with contamination from the uncontrolled release. However, given the degraded state of the oil, it was not possible to accurately identify the hydrocarbon components (i.e. to source match) and hence to unequivocally link the hydrocarbons at Ashmore Reef to the Montara uncontrolled release. Previous studies in the Timor Sea and North-west Shelf have shown there is a background presence of petroleum hydrocarbons (Burns et al 2001, 2010) which could originate from natural seeps, the oil industry, passing ships or discharge from fishing boats.

Irrespective of the source, current concentrations of total PAHs in the sediment samples were several orders of magnitude lower than the respective national Sediment Quality Guidelines (US EPA and ANZECC-ARMCANZ) that would constitute a risk to the environment.

Recommendations for further research

The current survey design provides adequate statistical power to develop into a long-term monitoring program, with the ability to characterise natural variability in the abundancy and diversity of key biota on the survey sites. Annual or biannual resurvey would detect changes equivalent to or greater than those measured in the first year.

Further assessment would be required to determine if the low coral recruitment rates measured at the three principal study reefs, relative to Scott Reef where a much more comprehensive long-term database on coral recruitment exists, represent the long-term average or are related to past disturbance and subsequent coral spawning stock recovery. Given the mean abundance of live coral at these reefs is moderate but increasing, it is reasonable to expect gains in both live coral cover and coral recruitment at all locations.

The reproductive sampling in this study has provided a significant increase in knowledge about coral sexual reproduction on Ashmore, Cartier and Seringapatam Reefs. The exact timing of coral spawning and the degree of multi-specific spawning synchrony remain unknown. A better characterisation of the timing of spawning and coral recruitment, along with improved measurement and modelling of currents, will be required to understand more clearly if reefs in this region are all highly isolated and rely on self seeding for renewal, or are sustained by connections between both emergent and submerged reef habitats.

While no major impacts on fish communities have been detected in the surveys, sublethal effects such as reduced growth may have occurred. In order to examine the possibility that the uncontrolled release may have affected juvenile fish growth rates, analysis of the age structure of fish communities would be required. This would require sampling selected fish species, ideally within the

next two years, with subsequent laboratory analysis of fish otolith bones to back calculate growth rates over the post-spill period.

In the event of future uncontrolled releases, sampling and analysis of sediment for hydrocarbons should be undertaken immediately. Since sampling only occurred five months (S6 Coral Reef) and ~fifteen months (S6B Coral Reef) after the Montara well was capped, it is unlikely that the true extent of any possible contamination of the shallow water sediments of the emergent reef systems of the Timor Sea will ever be known.

This study highlights the great value of having a long-term monitoring program. These provide data that can be used to derive causal links for observed patterns and most importantly, give researchers and managers the ability to determine whether observed changes are part of the natural variability in dynamic marine ecosystems, or reflect a response to the effects of anthropogenic stressors such as the unplanned release of oil into the ocean.

1. INTRODUCTION & BACKGROUND

The Montara Well Head Platform (MWHP) uncontrolled release (21st August – 3rd 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 banks 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.

In response to the triggering of the shallow coral reefs component of the Montara uncontrolled release scientific monitoring plan, developed by PTTEPAA and DSEWPaC, the lease operator, PTTEP Australasia (Ashmore Cartier) Pty Ltd (PTTEPAA), commissioned an initial survey of the closest shallow reefs (Heyward et al. 2010). The primary focus was an assessment of the status of shallow water benthos, particularly corals, in the Ashmore Reef National Nature Reserve and the Cartier Island Marine Reserve (hereafter called Ashmore and Cartier Reefs). The spill on the West Atlas drilling platform originated approximately 108 km from Cartier Reef and 175 km east of Ashmore Reef (Figure 1.1). Both Ashmore and Cartier are emergent fringing reefs at the western end of the Oceanic Shoals bioregion. Seringapatam Reef, another emergent reef in this bioregion, but approximately 195 km south-southwest of Ashmore Reef and not considered to be influenced by any spill related products, was selected as a reference site (see Figure 1.1). The initial study assessed the status of the sessile marine life around the reef edge zones, sampled sediments to allow testing for hydrocarbons and undertook a preliminary assessment of corals for evidence of reproduction at Ashmore Reef.

Heyward et al. (2010) found that the benthic communities were typical of shallow coral reefs and their condition consistent with previous independent benthic surveys at Ashmore and Cartier Reefs (Skewes et al.; Richard et al. 2009), although all three reefs were in the midst of a mild coral bleaching disturbance when the survey was conducted in April. The 2010 bleaching affected a minority of the coral community, although there was a differential effect between coral species and some individual species were strongly affected. Seringapatam Reef, the furthest away from the well head, was the worst affected by coral bleaching. This was the major aspect of significant difference in the status of benthic communities on these three reefs. There was good supporting evidence that region wide thermal stress caused the coral bleaching, which was also observed at Scott Reef, although a compounding effect from any pollution stress, though unlikely given the lower relative levels of bleaching at sites closest to the uncontrolled release, could not be absolutely ruled out. As the bleaching event was continuing at the end of the field survey period, the fate of bleached corals, which can recover, die, or become susceptible to disease after bleaching stress, remained unknown.

The composition and abundance of the major benthic groups measured in April 2010, provided no evidence of recent major disturbance at any of the reefs, suggesting that any effects of oil reaching these reefs was minor, transitory, or sub-lethal and not detectable with the sampling methods used. While there was no visual sign of oil or waxy oil on the sea surface around the reefs, or during shoreline walks on sandy islets at each reef, laboratory analysis of sediment samples detected some hydrocarbons at multiple sites at all three reefs. There were seven samples with higher hydrocarbon levels, in the range of 0.2-0.58 µg/g (or parts per million) with some indication of a similar oil composition to the Montara field reference sample. Five of these were found at Ashmore and one at

Cartier Reef, while the higher level sample from Seringapatam did not have the same chemical pattern. Based on this chemical evidence of a degraded crude oil (not bunker C or light diesel) above the background concentrations for the Timor Sea and the observations of surface slicks or sheens near the shallow reefs during the uncontrolled release event, it is reasonable to conclude that Ashmore and, to a lesser degree, Cartier Reefs were contaminated during the Montara uncontrolled release. However, as the sediment samples were collected approximately six months after the Montara uncontrolled release was stopped, natural attenuation processes had reduced the concentrations and changed the patterns so that full source matching, as is commonly performed on undegraded oils, was not possible.

A survey of coral reproduction in the first week of April, 2010 found very few coral species in reproductive condition. No gravid colonies of the dominant Acroporid species were found. Less than 10% of massive colonies in only a few common species, including *Goniastrea edwardsi* and *Favia pallida*, retained mature eggs. However, in two common brain coral species, *Goniastrea retiformis* and *Favites abdita*, approximately 30% of the Ashmore populations contained some mature eggs when sampled during the first two days of field work in early April. Impacts on annual coral reproduction were not able to be determined for the majority of species, as the timing of the survey (April 2010) probably occurred a month after the major annual spawning event, given March spawning were reported at other NW Reefs that year (Gilmour, Stoddart, pers. comm. to AJH). However, the very limited data on one species of hard coral observed to spawn during the study indicated normal spawning, gamete quality and embryological development.

Notwithstanding the lack of major impacts detected in 2010, uncertainties remained about more subtle potential effects and there remained knowledge gaps regarding coral reproduction and the recovery or otherwise of the bleached corals. A follow up survey was commissioned by PTTEPAA in 2011. The 2011 survey enabled a repeated assessment of the shallow reef benthos to ascertain the ongoing state of the coral communities, including the fate of 2010 bleached corals. In addition, an extended and more diverse selection of sampling was undertaken to see if processes of ongoing coral population renewal via sexual reproduction and recruitment were occurring. The 2011 surveys were broader in scope than the 2010 assessment, including comprehensive assessment of the fish communities associated with the benthic sites, as well as a re-sampling of reef sediments to follow up on the status of hydrocarbon detections noted in the 2010 report.

The work was undertaken by AIMS from the research vessel, RV Solander. It comprised a series of field expeditions to all reefs, beginning in February 2011 and concluding in May 2011. This enabled assessment of coral reproduction over a broader season than the 2010, while enabling repeat sampling at the same time of year as the 2010 surveys to assess any changes in coral abundance or hydrocarbon presence over the intervening year. This report is structured into separate chapters according to specific research objectives and results. These are benthic community status, coral reproduction, fish community status and sediment analyses.

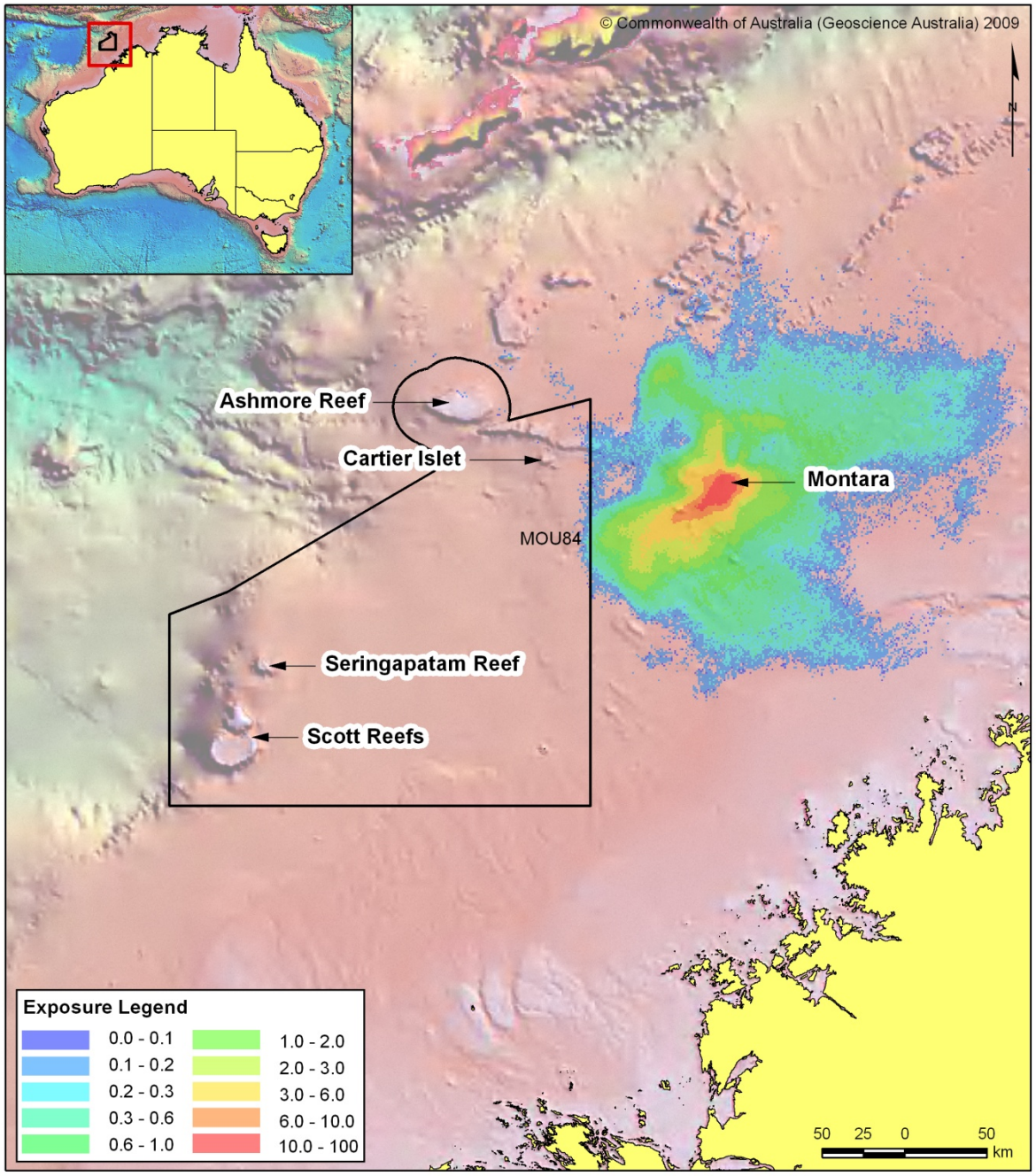

Figure 1.1 Location of the principal survey reefs Ashmore, Cartier and Seringapatam, in relation to a modelled exposure map of oil occurrence. Image of the modelled spill provided via PTTEPAA. This is a relative exposure map representing up to 99.9% of occurrences of visible surface oil associated with 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 spill incident. It is a summation of the area within which isolated patches of oil and wax were observed by aerial or satellite observations and additional oil spill trajectory modelling.

2. REEF BENTHIC ASSESSMENT

2.1 Introduction

The 2011 benthic survey repeated sampling at the locations established in 2010 (Heyward et al. 2010) at multiple reef edge locations around each of the three reefs. These study sites encompass a representative collection of habitats and differing exposure aspects. Eight marked, existing sites were available at Ashmore Reef, the largest of the three reefs, with six sites at both Cartier and Seringapatam Reefs. Photo transects sampling the benthic communities were undertaken just below the reef crest, along depth contour 3 m and 6 m below tidal datum. These transects cover the shallow outer reef edge habitat zone, which can support good coral cover on most reefs and which previous surveys have found to be important areas of coral habitat at Ashmore, Cartier and Seringapatam Reefs. These shallow reef edge sites were also where water-borne pollutants, carried by winds and surface currents near or on the sea surface, might have first come into contact with the reef benthos.

In the 2010 survey, typical coral reef organisms were encountered at the three reefs, which shared broadly similar benthic community structure. Turf algae and hard coral were the major components at all reefs. The shallowest areas, on the reef flats adjacent to the dive transects, had consistently low coral cover (3.58 -7.13% mean cover). This also was generally the case in the shallow reef crest zone exposed to breaking surf, especially at Cartier and Seringapatam Reefs (8.88 and 4.10% mean cover respectively), while the reef crest zone was more variable and generally had higher live coral cover at Ashmore Reef (range 0.0 -60.0 %, mean live cover 21.38%). All three reefs had the highest mean live coral in 2010 on the 3 m and 6 m transects (range 20.43-36.50%), so these depths were selected for the 2011 monitoring survey. Coral cover was known to be variable around each reef at Ashmore and Cartier, and more so at Seringapatam. There were a few locations supporting coral at all three reefs that averaged 40 - 50% live cover across the entire survey site. This is a relatively high mean live coral cover, comparable to coral cover measured on healthy, recently undisturbed reefs in other regions, such as the outer slopes of the Great Barrier Reef. At Ashmore and Cartier Reefs, at the finer spatial scales of individual 20 m transects, maximum live coral cover reached 64% and 65% respectively at 3 m, while the highest cover observed on an individual transect at Seringapatam was 58% at 6 m.

While biota in 2010 appeared to be normal and most corals appeared healthy, some coral species were either partially or completely bleached. This bleaching was recent and ongoing during the April 2010 assessment, as very few corals that were severely bleached showed signs of mortality (algal films developing on extremities). AIMS temperature records from *in situ* recorders previously deployed at Ashmore Reef indicated abnormally high seawater temperatures above 32˚C beginning in early to mid-March 2010. This coral bleaching, which appeared to be a region-wide phenomenon associated with abnormally high seawater temperatures, was the major difference in the status of benthic communities on these three reefs. The effect was generally restricted to the 3 m and 6 m reef slope sites where coral cover was higher, being greatest at 3 m, and not a significant component of the low coral cover reef flat habitats. This bias is due to the distribution of sensitive species such as *Pocillopora edouxi, Galaxea fascicularis* and the fire coral *Millepora*. At locations where these types of coral were more abundant, particularly for *P. edouxi* on the upper reef slope, the overall level of bleaching was higher. Most Acroporid corals, which were the dominant group at all sites, showed a low incidence of bleaching. Bleaching levels, measured as a percentage of total live coral, were significantly higher at Seringapatam Reef (≈15% of corals at 3 m), which is the farthest from the Montara release, than at Ashmore and Cartier Reefs (both having approximately 3% of corals at 3 m bleached).

The current shallow reef benthic survey by repeating the sampling done in 2010 was designed to measure changes in the composition and abundance of the major benthic groups after a year, including a reassessment of corals bleaching, and make comparison between Ashmore and Cartier Reefs, closer to the uncontrolled release source, with Seringapatam Reef.

2.2 Methods

2.2.1 Site selection

Previous marine biological surveys of Ashmore and Cartier Reefs (Skewes et al. 1999; Richards et al. 2009; Heyward et al. 2010) found most of the significant coral cover around the outer reef flat, crest and slope. The current survey of Ashmore, Cartier and Seringapatam revisited the same sites established on the upper outer reef slopes for the 2010 survey (Heyward et al. 2010). The locations were originally selected to cover a broad and representative range of habitats that might be affected by the uncontrolled release and a subset were also, to the degree possible, co-located within habitats previously assessed status at Ashmore (see Richard et al. 2009). A minimum of six sites at a two depths for each reef was sampled.

At each survey site, replicate marked transects (6 x 20 m) were established by the dive team at 6 m and 3 m below the estimated low tide datum, calculated from the national tide tables (Ashmore & Cartier - port 62740, Seringapatam - port 62730; Seafarer tides 2010 ver. 1.5.79, Australian Hydrographic Service). These transects were established within a nominal habitat length of around 200 m along each depth contour.

The sites were relocated using GPS coordinates from Heyward et al. (2010) for the start and end positions, with divers then searching until they found small subsurface relocation floats, which had been attached to the seabed to mark the location and depths of the 2010 transects (see Figures 2.1, 2.2). Transect tapes were then relocated at the correct depths and locations within the site. Waypoints for the start and end of each 6 x 20 m contour group were confirmed using GPS.

2.2.2 Transects

Diving was conducted from 5.8 m inflatable tenders using SCUBA incorporating spare bailout bottles, with a surface line and float marker to each dive team, monitored by a qualified boatperson. A medic, chamber operator and recompression chamber were in attendance nearby onboard RV Solander. On each 20 m transect, standard AIMS LTM photo survey methods were employed, with a series of 10 megapixel digital photo images captured along each transect (Jonkers et al. 2008).

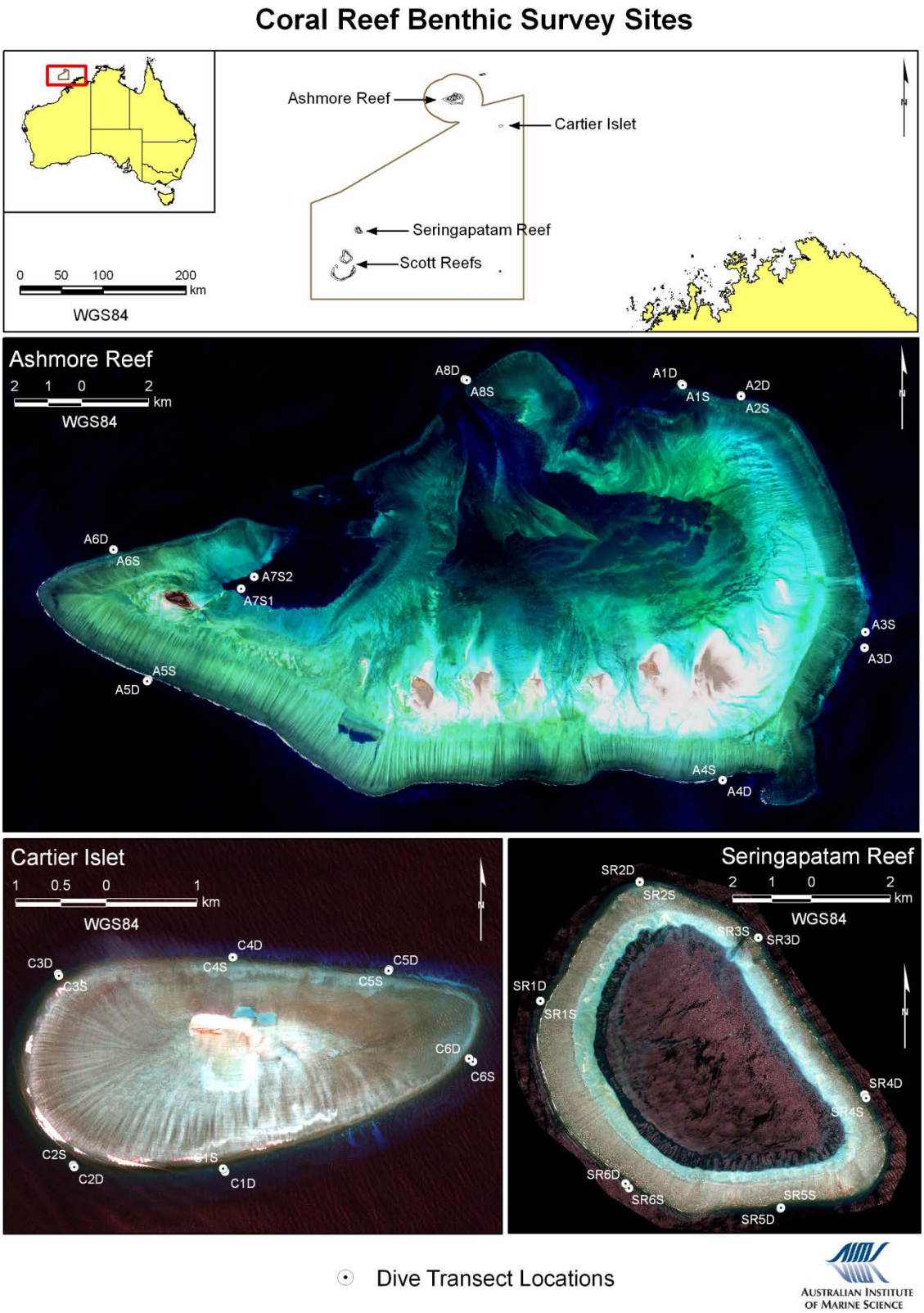

Figure 2.1. Benthic survey site locations at Ashmore, Cartier and Seringapatam Reefs.

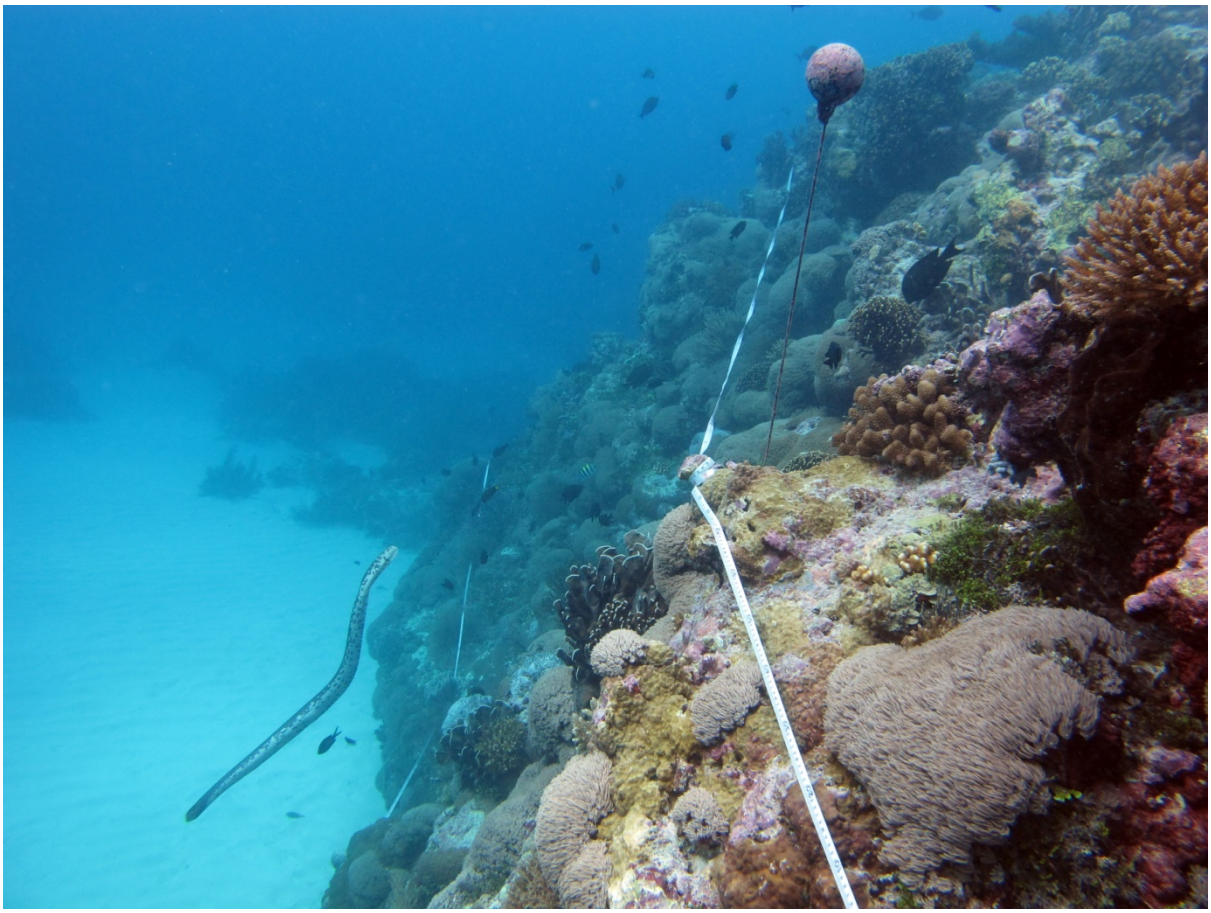

Figure 2.2. Cartier Reef benthic survey transect example: the 2011 survey revisited reef locations established in the 2010 survey, using GPS coordinates and divers searching target depths to find small subsurface floats (as shown in photo) left on the survey contours in 2010. Survey transects were then re-established at the correct depths through the same habitats.

2.2.3 Image analysis

The approach to image analysis is the same as previously reported by (Heyward et al. 2010) in a survey of the same sites. For this report, the survey transects established at all depths and all sites were assessed to provide comparative measures of the benthic community at Ashmore, Cartier and Seringapatam Reefs e.g. Figure 2.3. At each site, for the 3 m and 6 m deep transects, twenty photos along each of the six fixed transects was analysed, using the standard AIMS ReefMon point-intercept and database management software (Jonker et al. 2008). Five points per image were classified. This sub-sampling provided twenty images per transect and 120 at each depth, with data for each site generated from 600 points along each depth contour.

2.2.4 Statistical and graphical analysis

Descriptive summaries were produced at site and reef level for major benthic groups. The coral cover was summarised through bar charts and tables as mean coral cover (+ SE) for the major benthic groups for different years, reefs, sites within reefs and depths.

The mean difference in coral cover and turf between years for each reef was compared using t-tests. All data was transformed using Logarithm +1.

Power analysis was used to investigate the degree of power there is to detect a significant difference in percent change in coral cover over 10 years (Zar 2010). It was assumed there was a linear relationship in the change in coral cover between years. Following convention, the power was set at $(1-\beta) = 0.80$ and the significance level was set at $\alpha=0.05$ to calculate minimum detectable difference in coral cover. The 2010 and 2011 percent coral cover data was used as input into the power calculations, including the observed slope (percent change in coral cover) and standard deviation of the change in coral cover.

The coral cover at family level was summarised using bar charts (Figures 2.12-2.17), which shows the mean (+SE) composition of coral cover at family level for each reef, sites, years and depths. The mean differences in coral cover was compared using analysis of variance (ANOVA) (Zar 2010), in which differences in coral families, reefs, depths and years were investigated. If there was a significant difference in main effects or interactions, then a post-hoc two sample t-test was conducted.

The coral bleaching classification for dominant hard coral families was summarised into tables, showing coral bleaching classifications for each year, dominant hard coral families, reef, and depth. Corals were classified as healthy in appearance, partially bleaching or fully bleached during the point intercept analyses.

A logistic regression was applied to explore the probability of coral bleaching (partial and total bleaching combined) between years, reefs, coral families and depths. Where zero probability defines no bleaching has occurred. Due to small sample sizes, not all interactions could be investigated in the same model. Therefore the model with significant interactions was displayed. A Fisher's Exact test was applied to compare the number of corals that were classified as benthic cover bleached (partial and total bleaching combined) and not bleached between years for each reef, dominant coral families and depth.

All analysis was conducted using the statistical package R (R Development Core Team 2011).

2.3 Results

The abundance and relative contribution of the major benthic groups was found to be very similar in 2011 to those reported in 2010 (Figures 2.4-2.6). The sites were almost completely covered with life, with bare substrate accounting for less than 2% of the area. Turf algae and hard coral were the dominant biota at all reefs, accounting for 63-76% of the benthic cover. The other major benthic groups, macroalgae, sponges, soft corals and coralline algae each contributed 2-7%, except for soft corals at Cartier Reef. There they were important in both years, increasing slightly from 18.26% to 18.75% cover in 2011 (Figures 2.5, 2.9).

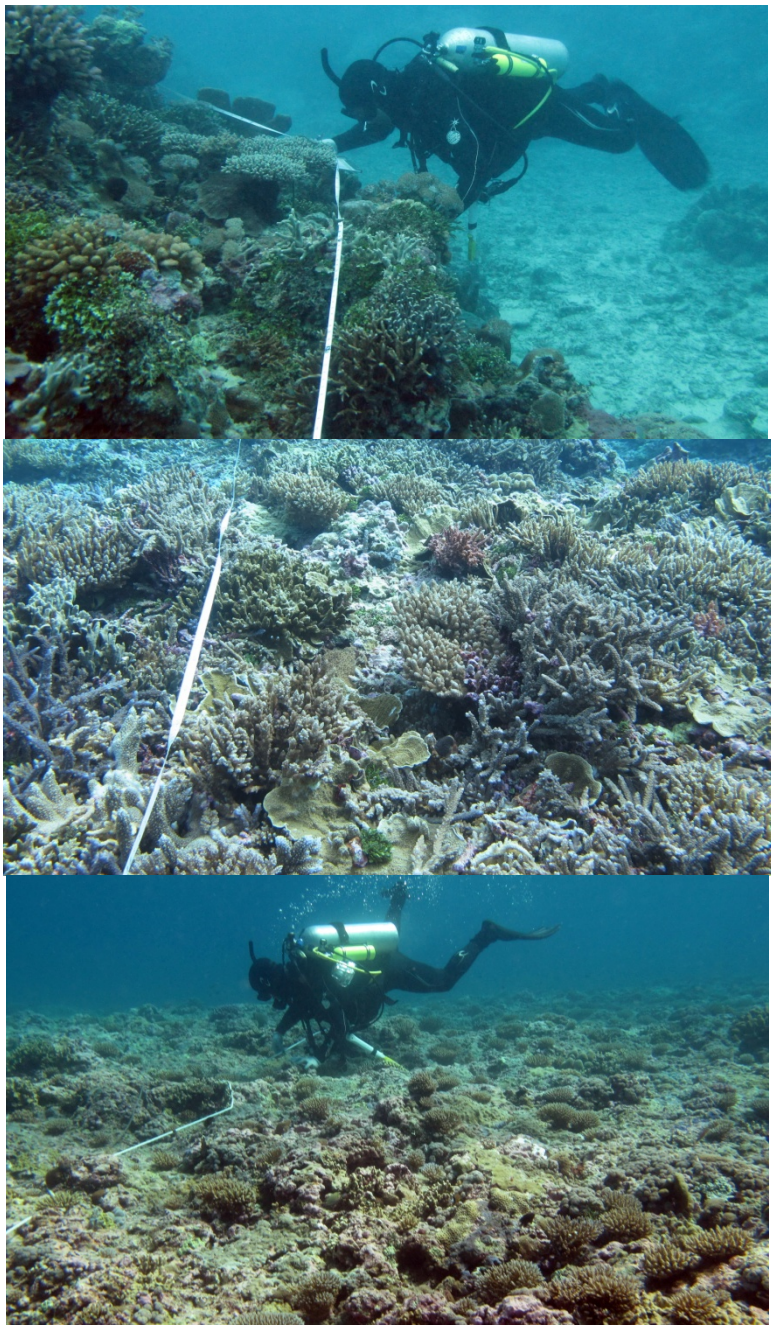

Figure 2.3. Ashmore Reef (top), Cartier Reef (middle) and Seringapatam Reef (bottom) 3 m depth habitat examples.

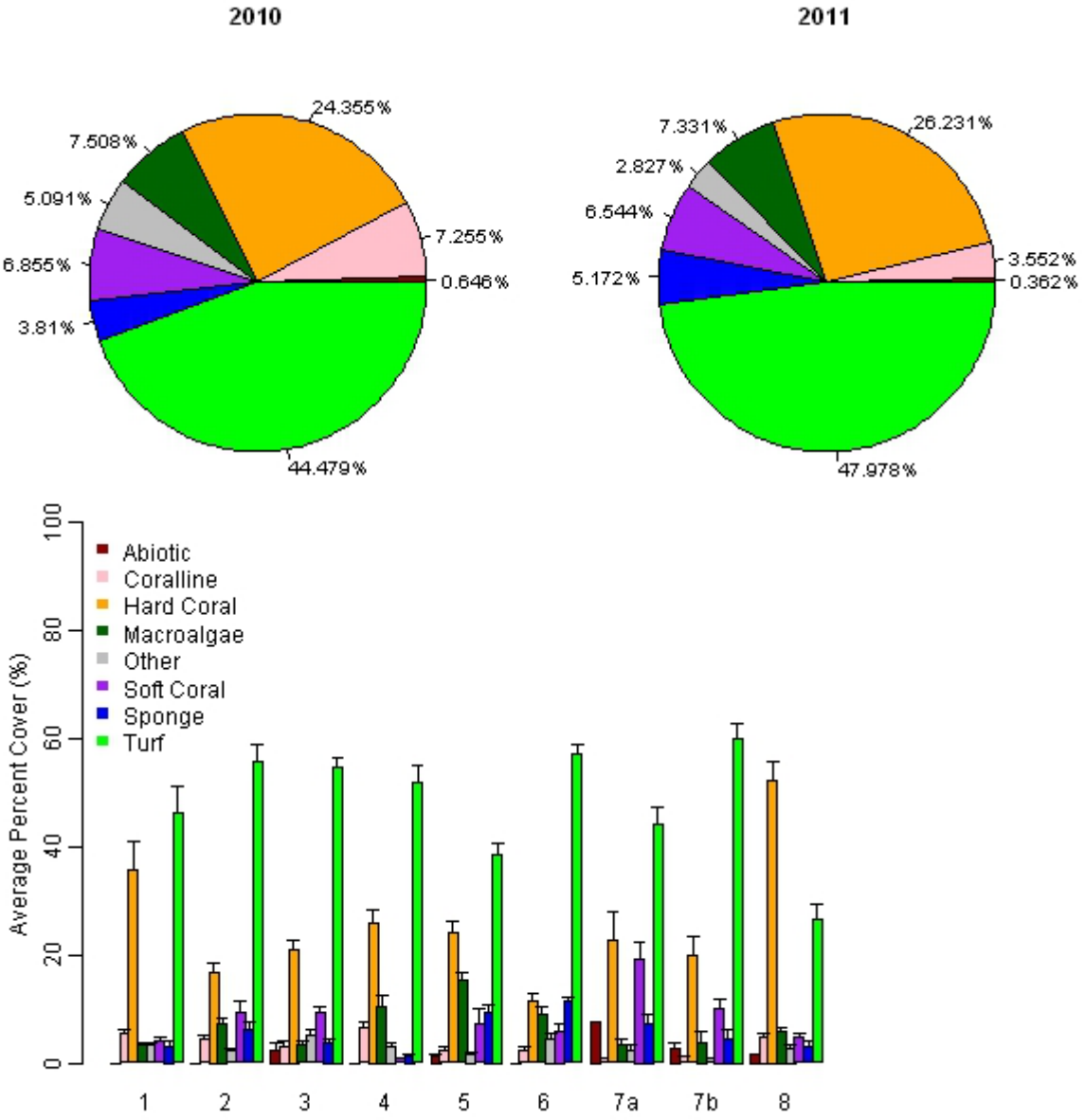

Figure 2.4. Ashmore Reef. Top – Pie chart of benthos groups for 2010 and 2011. Below – Histograms of 2011 mean abundance (+ SE) expressed as percent cover per 20 m transect, of major benthic groups averaged for all depths at each survey site. Data on the horizontal axis refers to the location of the site A1–A8.

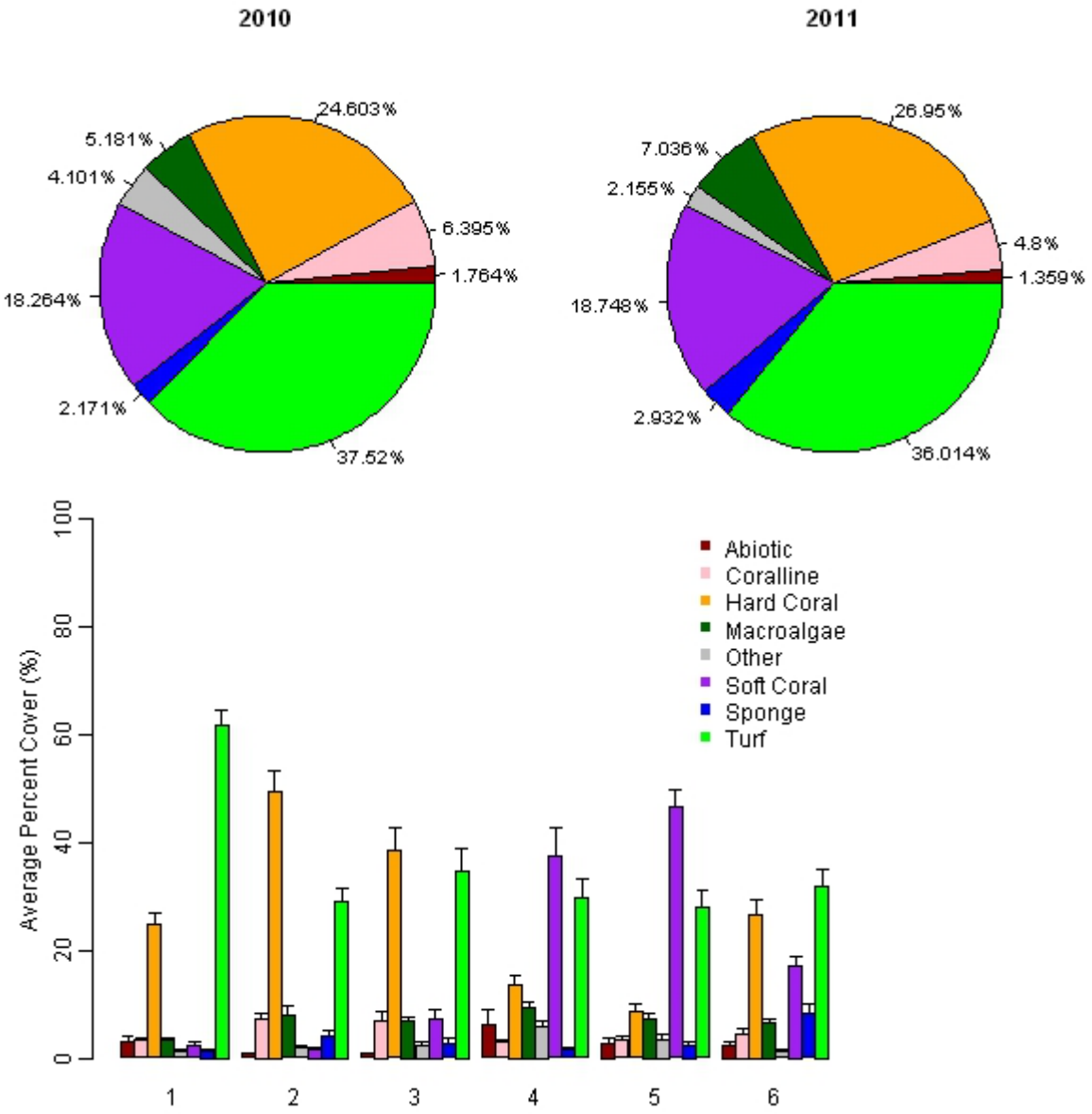

Figure 2.5 Cartier Reef. Top – Pie chart of benthos groups for 2010 and 2011. Below – Histograms of 2011 mean abundance (+ SE) expressed as percent cover per 20 m transect, of major benthic groups averaged for all depths at each survey site. Data on the horizontal axis refers to the location of the site C1–C6.

Overall, mean hard coral increased in abundance at all three reefs, but gains were modest (2.7% mean increase overall) and not statistically significant (Table 2.1). Trends with the other major group, turf algae, were also not significant, with slight increases in abundance at Ashmore and Seringapatam but a slight decrease at Cartier Reef (Tables 2.1, 2.2). These rates of annual change are in the middle range of those reported in the past from Scott Reef (Heyward et al. 1998) but lower for Ashmore than interpolated between 2005-9 by Ceccarelli et al. (2011). A power analysis using the current survey design indicates that at current the rate of mean annual increase in coral cover is 2.6%. A another year sampling is required in order to achieve significant 95% confident detectable difference in coral cover (Figure 2.7).

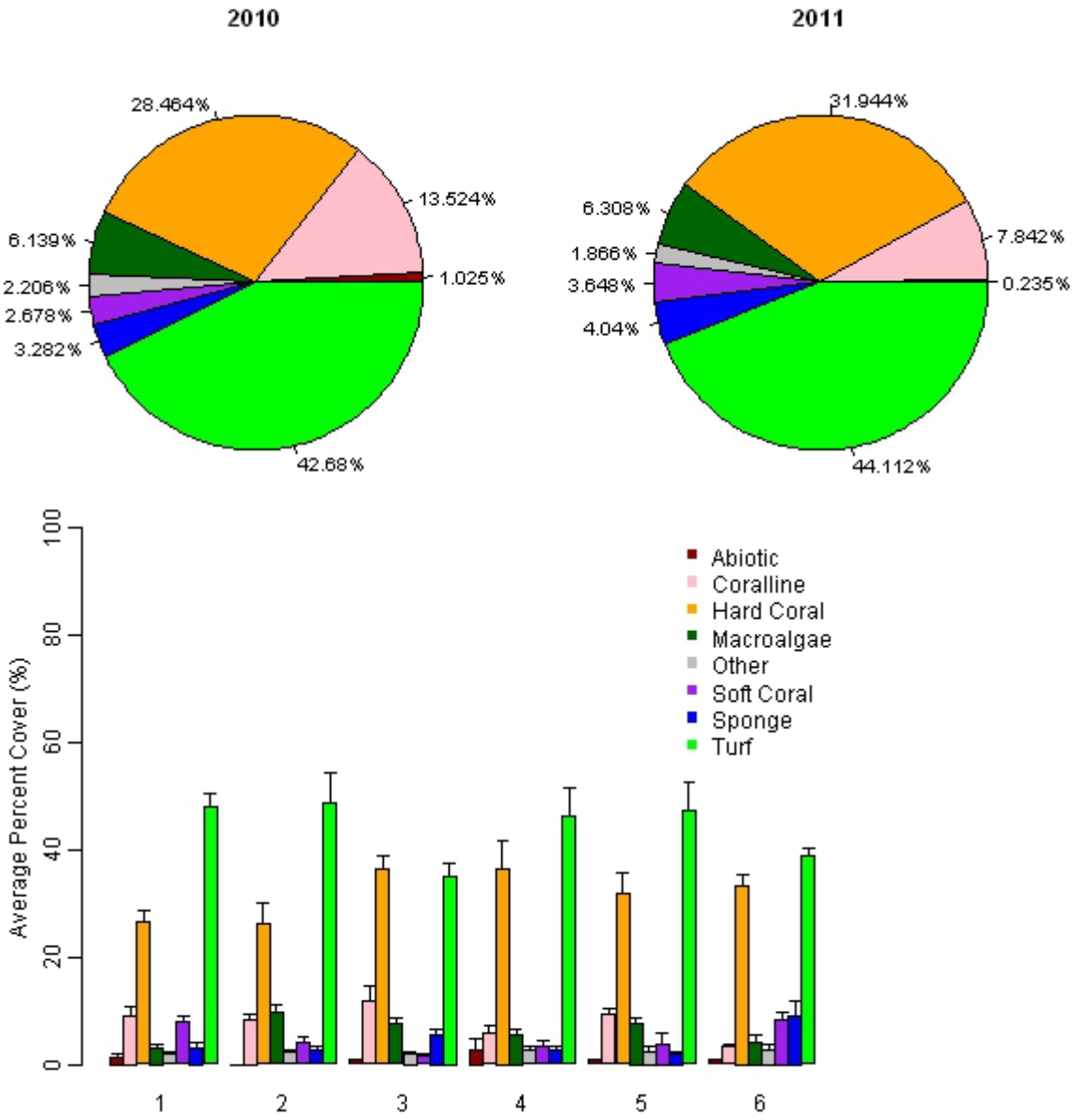

Figure 2.6. Seringapatam Reef. Top – Pie chart of benthos groups for 2010 and 2011. Below – Histograms of 2011 mean abundance (+SE) expressed as percent cover per 20 m transect, of major benthic groups averaged for all depths at each survey site. Data on the horizontal axis refers to the location of the site SR1–SR6.

Table 2.1 T-test results comparing mean % Hard coral between 2010 and 2011 for each reef.

	Mean 2010	Mean 2011	t	df	p-value
Ashmore reef	24.3551	26.23115	-0.8896	187.298	0.3748
Cartier reef	24.60347	27.32986	-0.9715	140.902	0.333
Seringapatam	28.46417	31.94444	-1.6493	141.87	0.1013

Table 2.2 T-test results comparing mean % Turf between 2010 and 2011 for each reef.

	Mean 2010	Mean 2011	t	df	p-value
Ashmore reef	44.47927	47.97812	-1.6346	188.852	0.1038
Cartier reef	37.52014	36.01389	0.5432	141.105	0.5878
Seringapatam	42.68028	44.11181	-0.608	140.482	0.5442

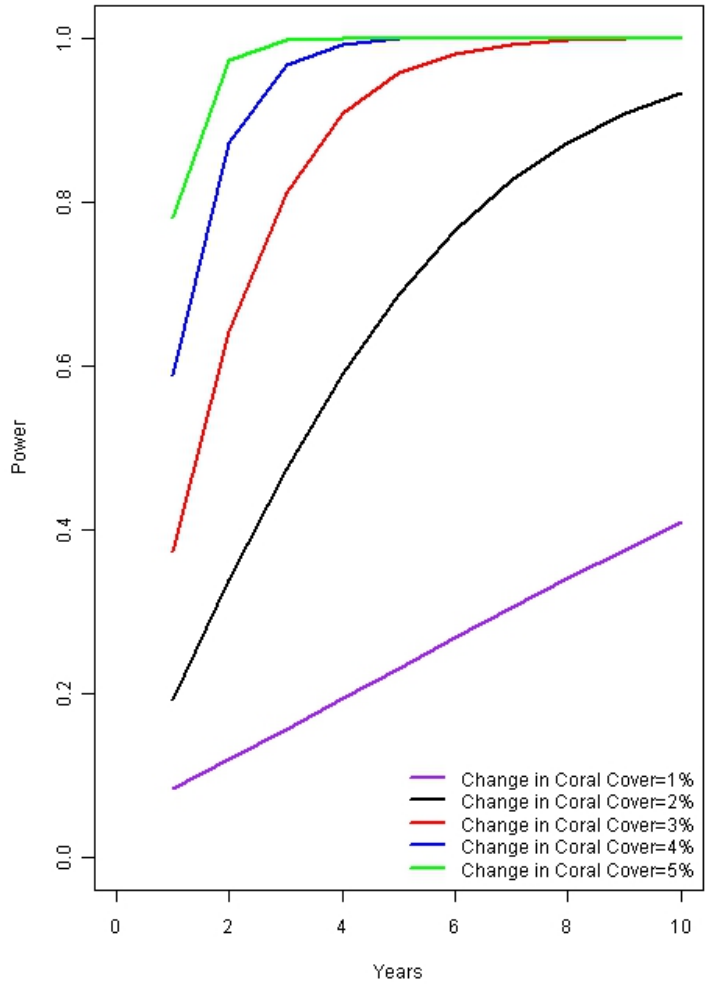

Figure 2.7. Power analyses providing the degree of power over 10 years for different percent change in coral cover.

Currently the rate of mean annual increase in coral cover is 2.6%. Another year sampling is required in order to achieve significant 95% confident detectable difference in coral cover. If there is a 5% change in coral cover next year, then there is a 0.97% certainty that there is a real and significant change (0.05). However, at the other extreme, more than 10 years of accumulated improvements would be required before a subsequent annual 1% change is detectable as significant.

There was significant variability in the composition of the benthic communities at different locations around each reef and in the changes observed at individual locations within reefs over the twelve months. Hard corals varied with location and between the 3 and 6 m depths (Figures 2.8, 2.10, 2.11). The highest coral cover for Ashmore was at location A8 on the central northern side (60.17%) on the 3 m depth contour, while at Cartier, the highest coral cover (56.05%) was found on the 6 m depth contour. This was also the case at Seringapatam (48.33% @ 6 m), where there was a significant increase in coral cover from 3 m to 6 m (Table 2.3).

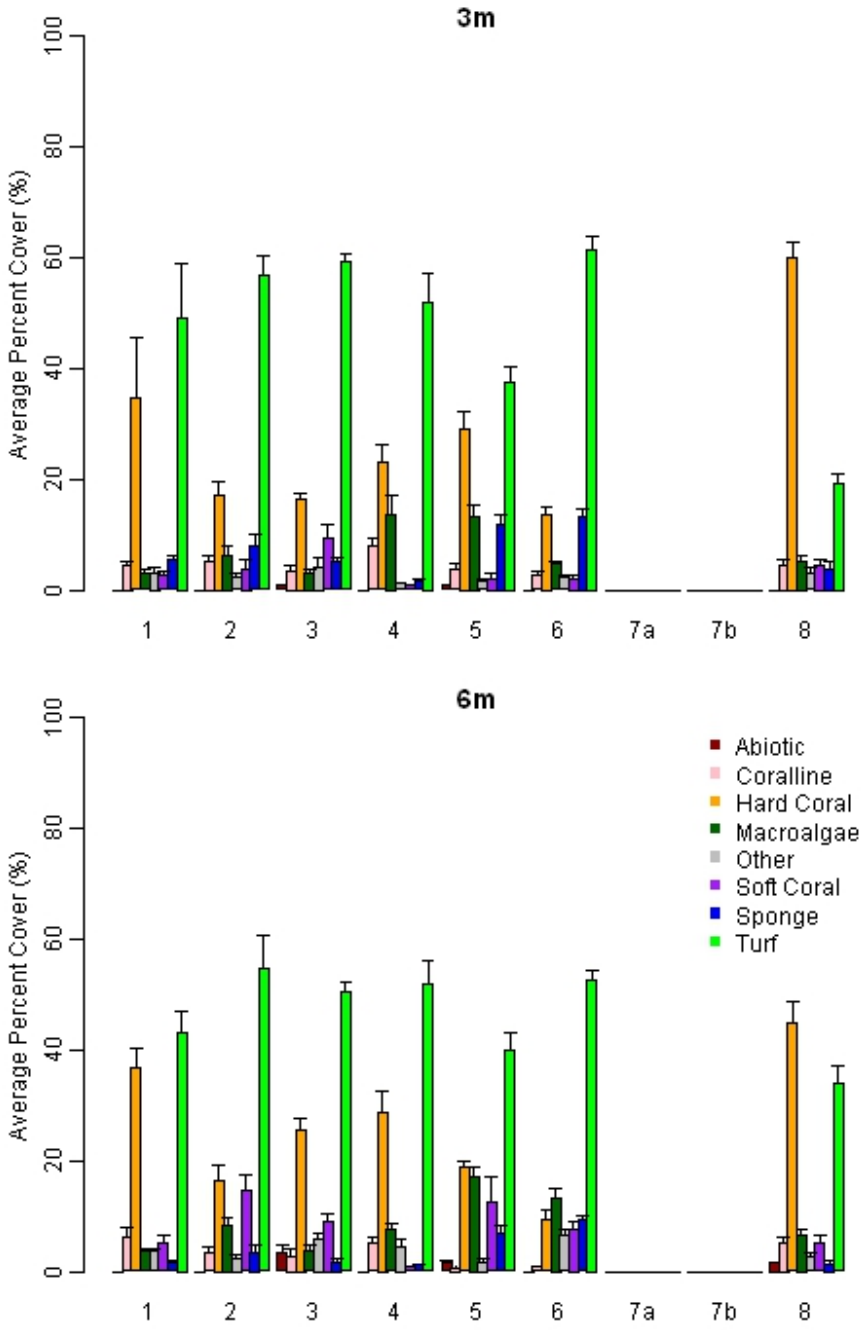

Figure 2.8. Ashmore Reef in 2011– abundance of major benthic groups on the 3 and 6 m transect sites.

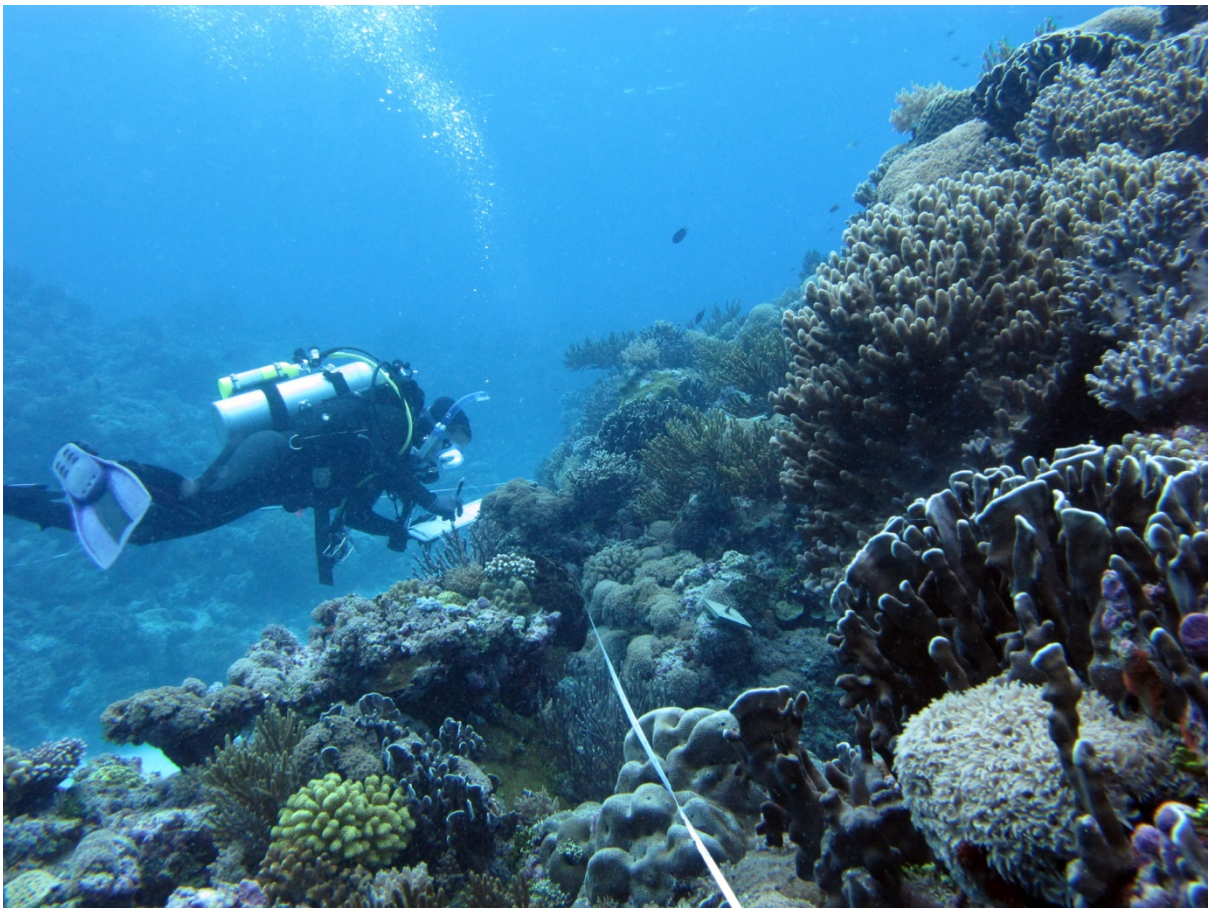

Figure 2.9. Cartier Reef, mixed hard and soft coral community. Location C5 (refer Figure 2.1) 6 m. Soft coral were most abundant at this and the adjacent C4 location on the northern side of Cartier Reef.

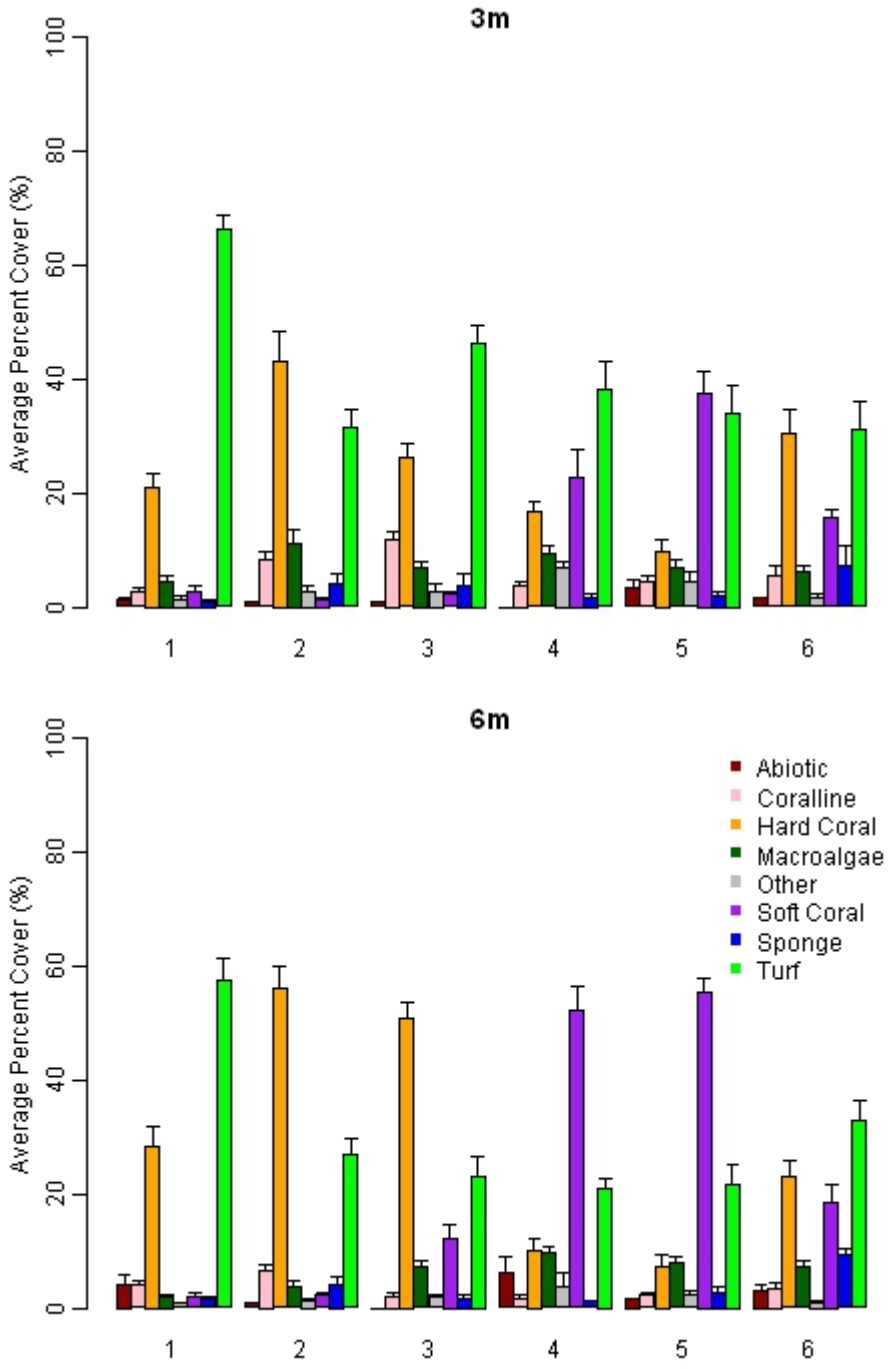

Figure 2.10. Cartier Reef in 2011– abundance of major benthic groups on the 3 and 6 m transect sites.

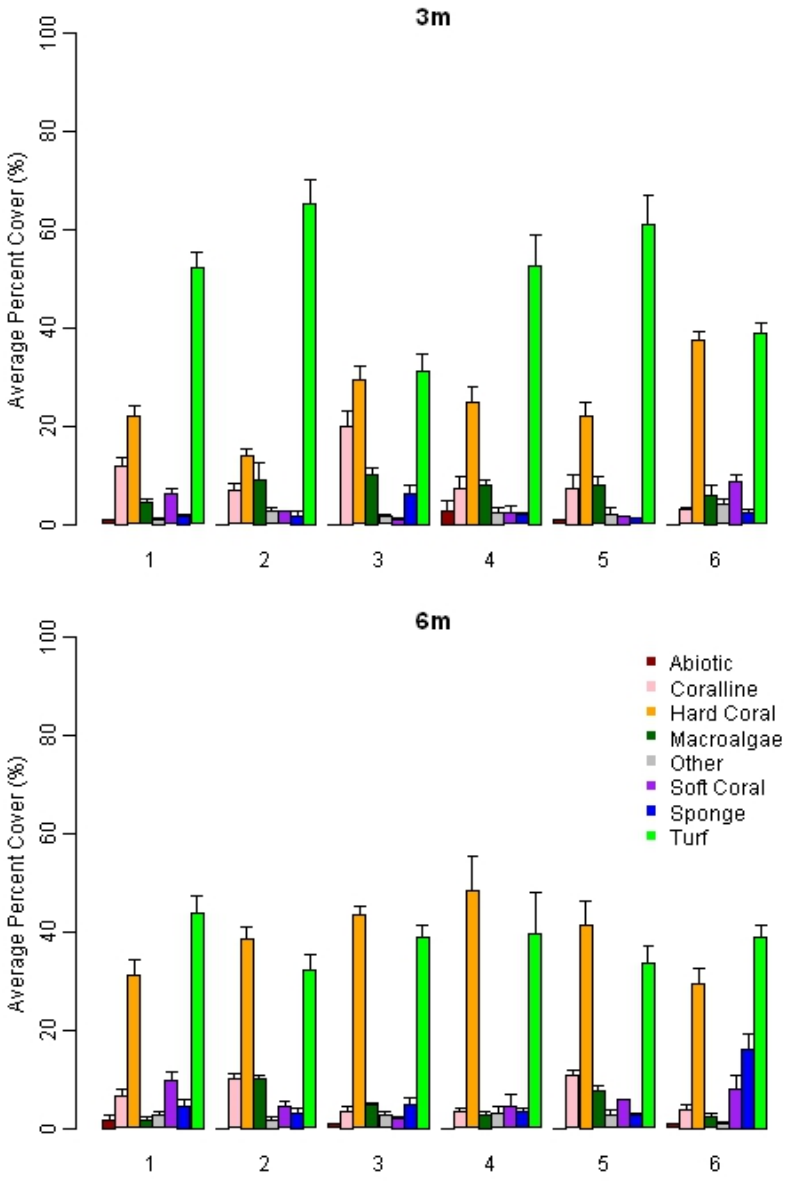

Figure 2.11. Seringapatam Reef in 2011 – abundance of major benthic groups on the 3 and 6 m transect sites.

Table 2.3. Coral cover versus depth within reefs. T-test summary table comparing coral cover between each reef and depth.

Reef	mean cover 3 m	mean cover 6 m	t	df	p
Ashmore	1.611	1.615	0.076	693.987	0.939
Cartier	1.538	1.658	1.787	581.661	0.075
Seringapatam	1.644	1.958	4.677	574.025	**<0.0001**

2.3.1 Coral Families

The relative importance of the dominant coral families has remained unchanged between 2010-11 (Figures 2.12-2.17, Table 2.4). The Acroporidae are the overwhelmingly dominant family, typically accounting for 2-3 times the percent cover as the other major families. The bulk of remaining coral cover consisted of Poritidae, Faviidae and Pocilloporidae. Within the Acroporiidae, the genus Montipora continues to contribute more than *Acropora* spp on all reefs (Table 2.5).

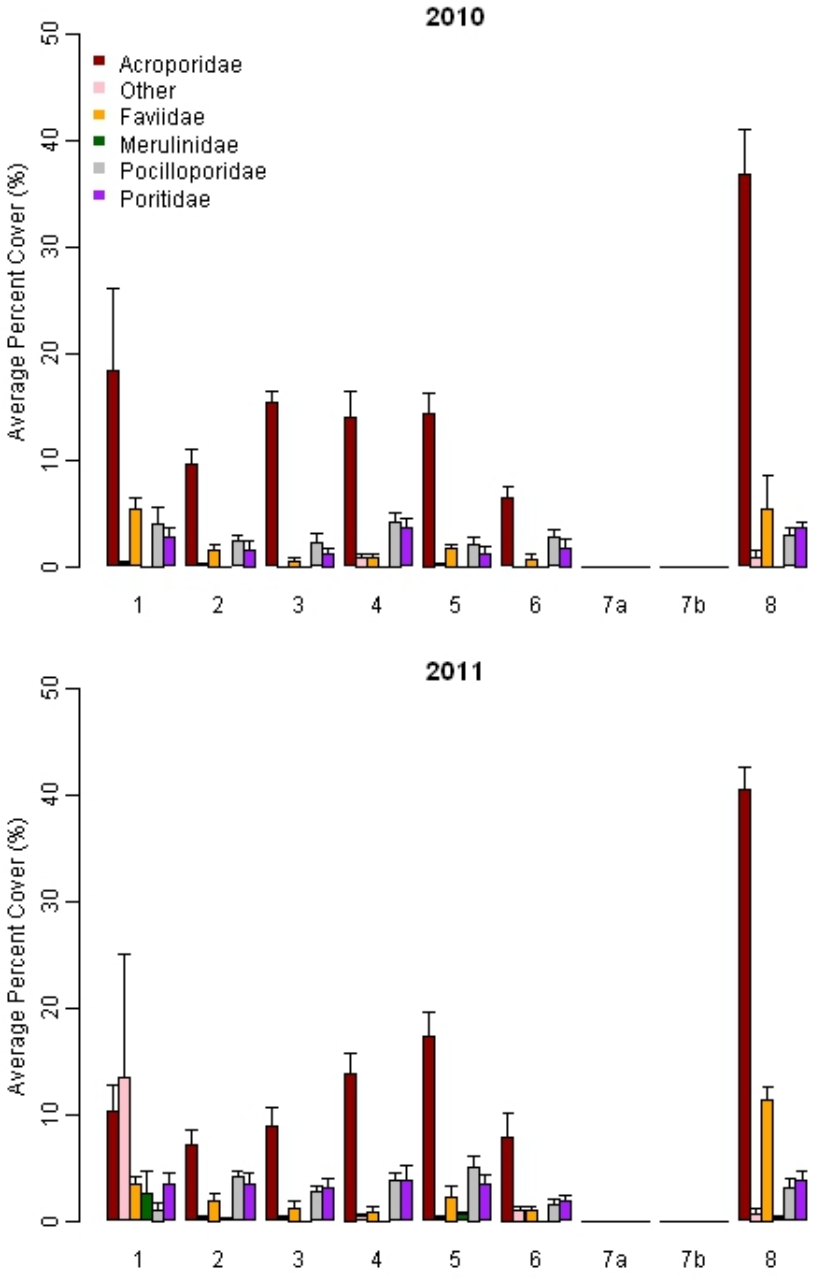

Figure 2.12. Ashmore Reef in 2010 and 2011 – abundance of dominant coral families on the 3 m fixed transects.

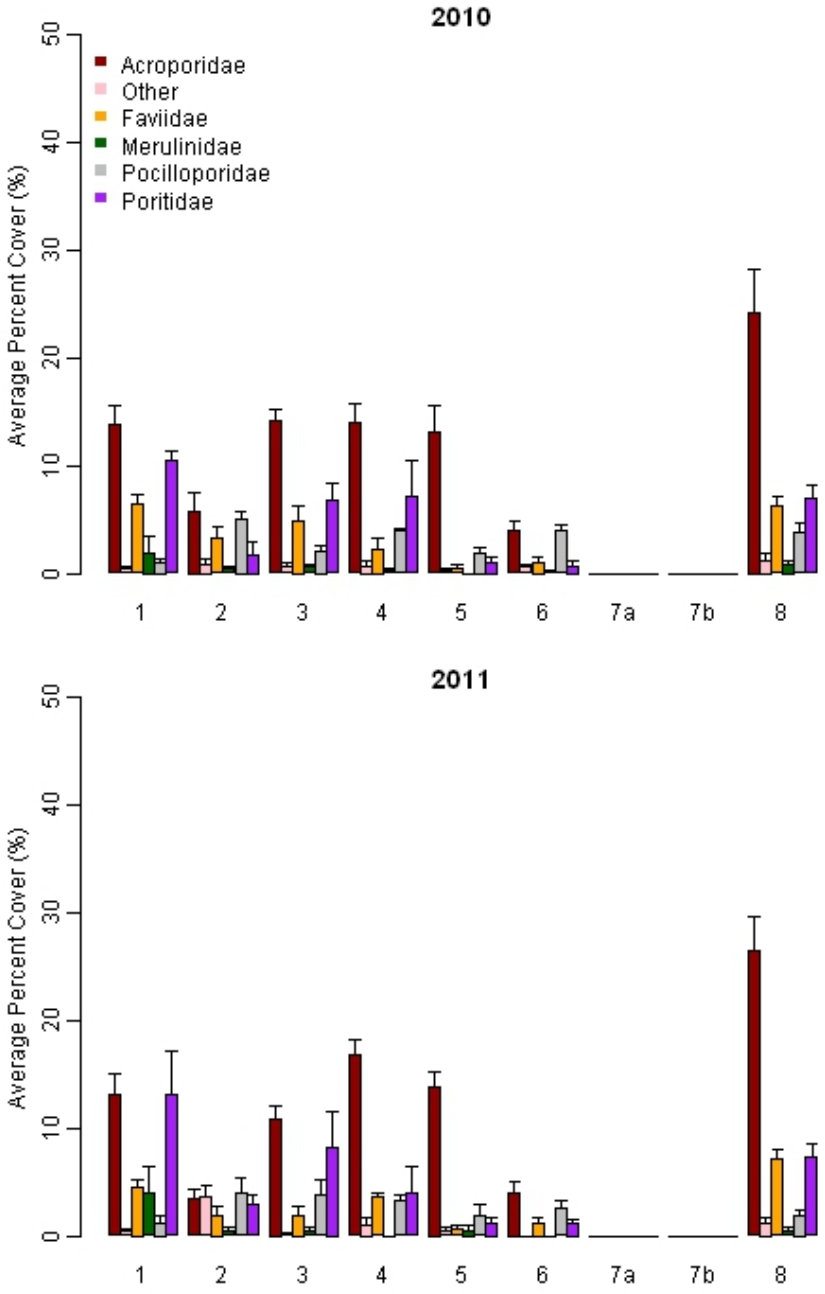

Figure 2.13. Ashmore Reef in 2010 and 2011 – abundance of dominant coral families on the 6 m fixed transects.

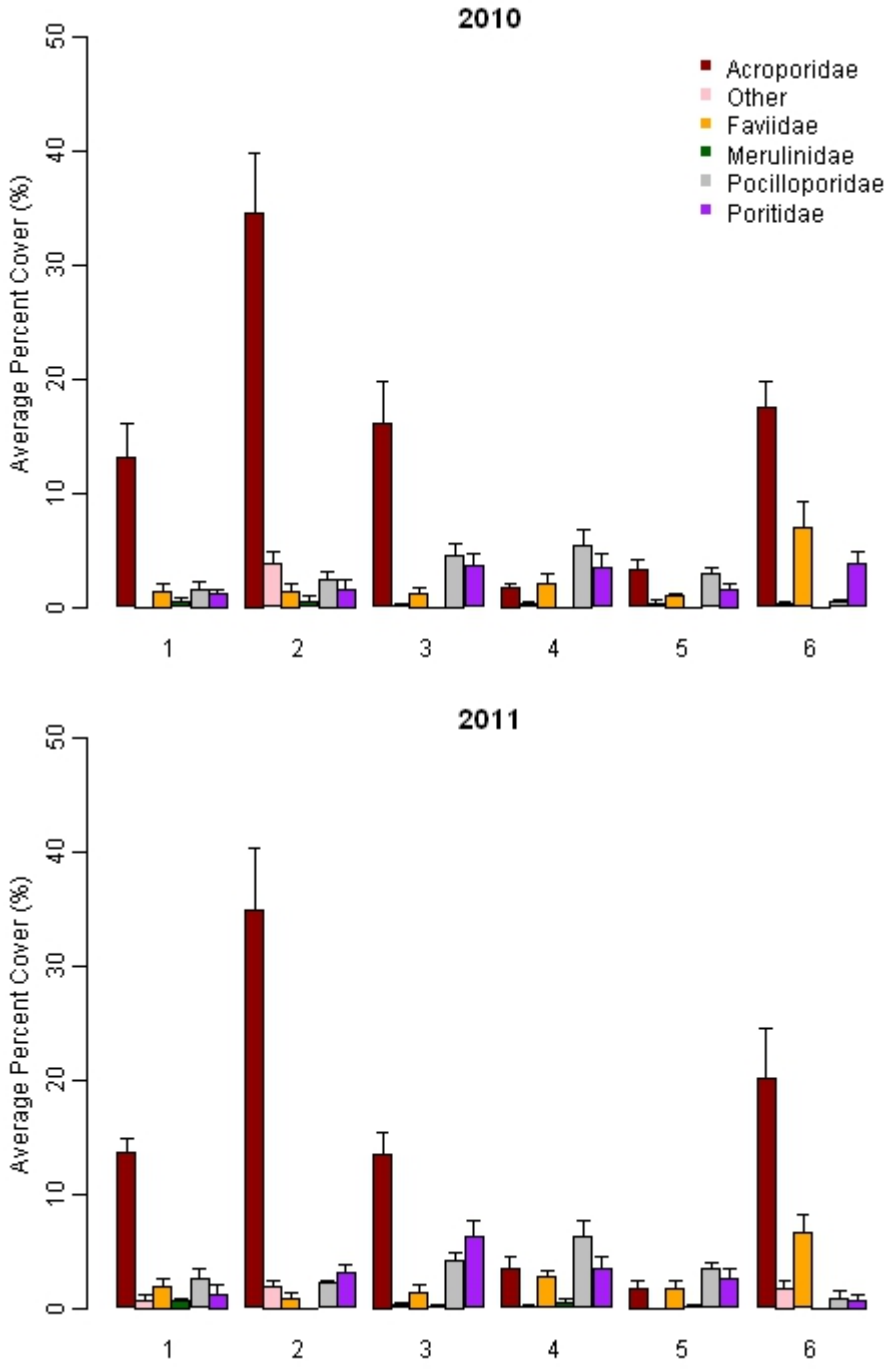

Figure 2.14. Cartier Reef in 2010 and 2011 – abundance of dominant coral families on the 3 m fixed transects.

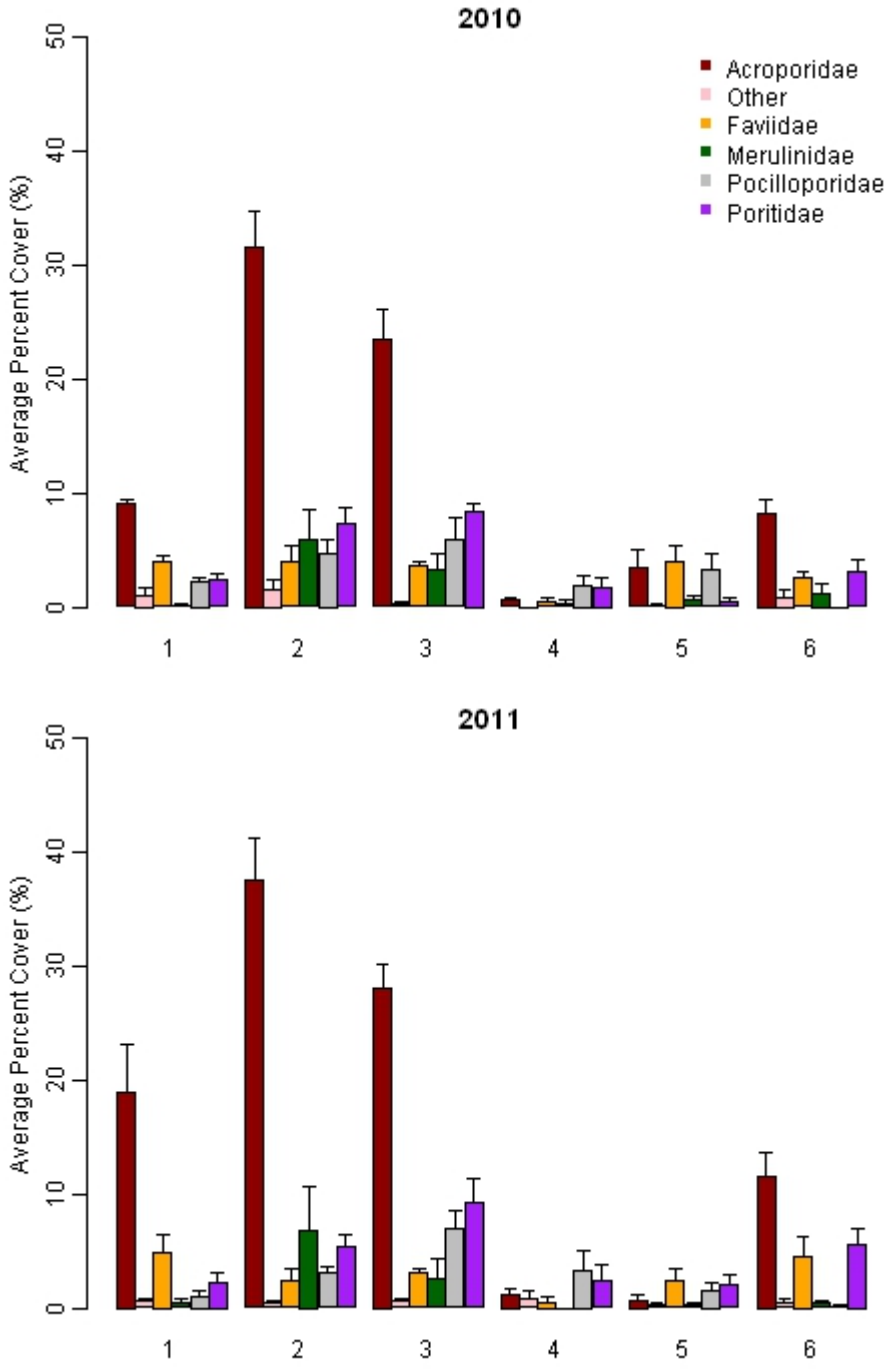

Figure 2.15. Cartier Reef in 2010 and 2011 – abundance of dominant coral families on the 6 m fixed transects.

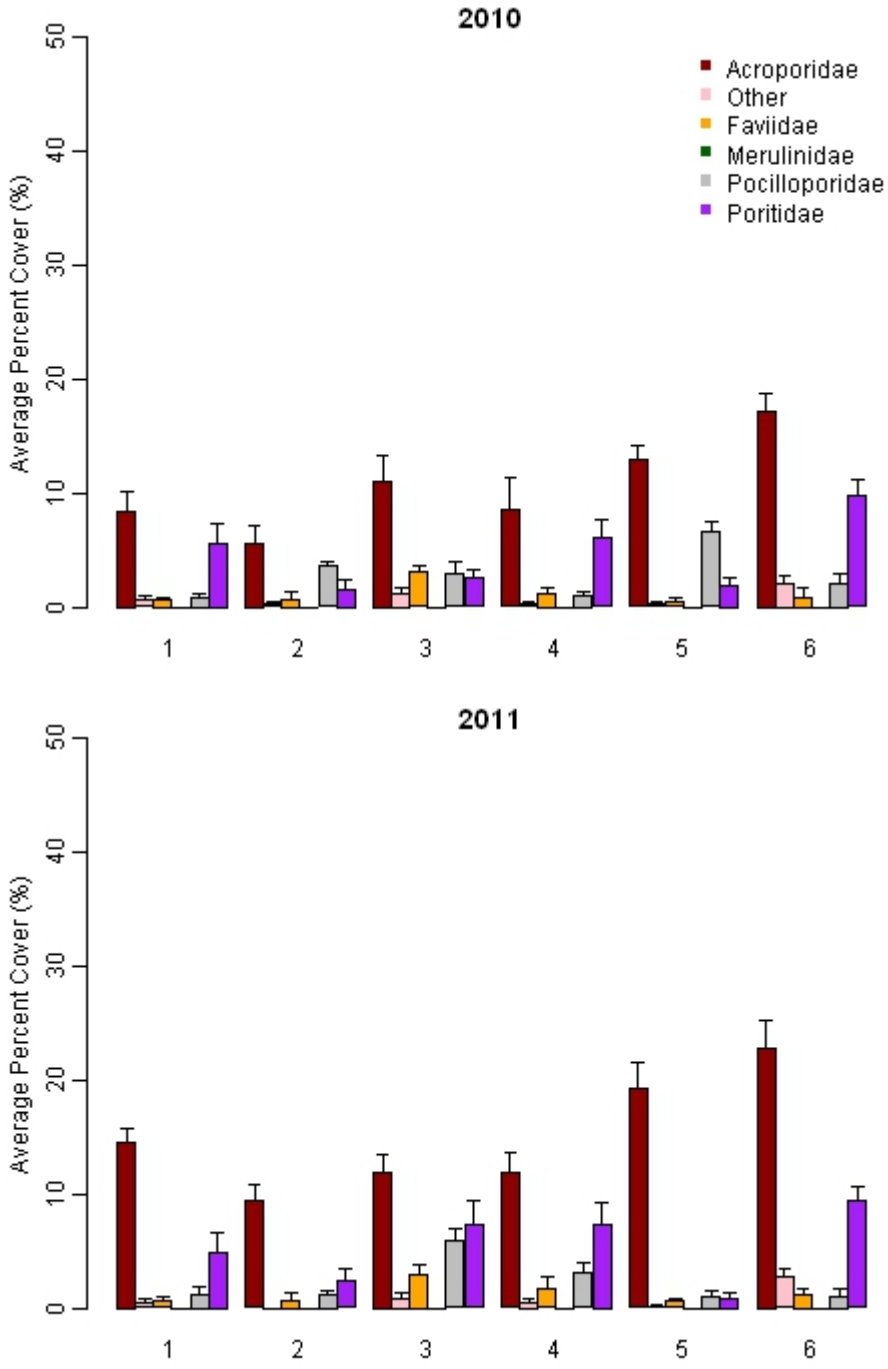

Figure 2.16. Seringapatam Reef in 2010 and 2011 – abundance of dominant coral families on the 3 m fixed transects.

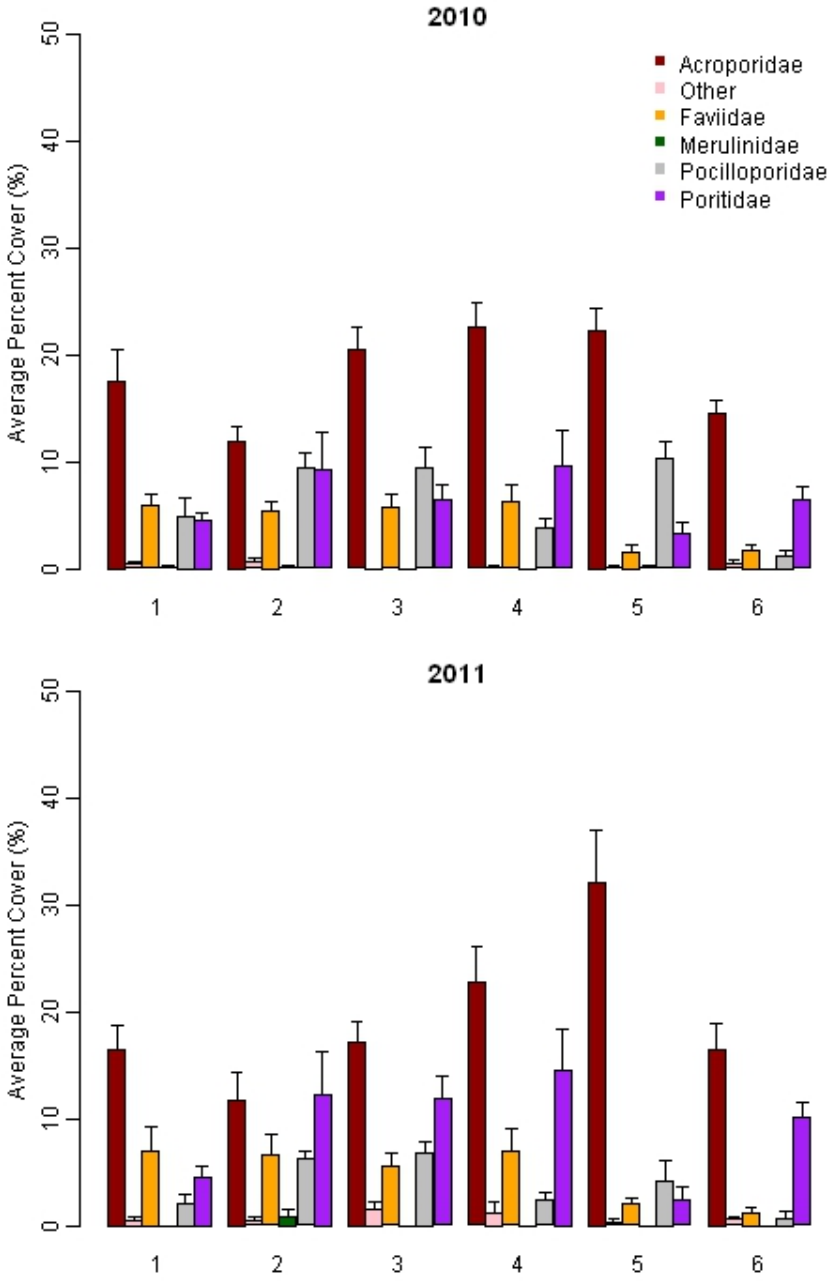

Figure 2.17. Seringapatam Reef in 2010 and 2011 – abundance of dominant coral families on the 6 m fixed transects.

Table 2.4. Mean percent coral cover for each reef and family.

	Ashmore Reef	Cartier Reef	Seringapatam Reef
Acroporidae	13.247	15.893	15.897
Faviidae	4.491	3.604	4.174
Merulinidae	2.411	3.637	1.5
Pocilloporidae	3.277	3.841	4.603
Poritidae	4.752	4.266	7.302

Table 2.5. Mean (± SE) percent coral cover for *Acropora* and *Montipora* (within family Acroporidae) for each reef, year and depth.

		Ashmore Reef		Cartier Reef		Seringapatam Reef	
		2010	2011	2010	2011	2010	2011
Acropora	3 m	2.855 (±0.207)	3.015 (±0.247)	3.684 (±0.615)	2.721 (±0.331)	1.672 (±0.179)	2.034 (±0.204)
	6 m	2.817 (±0.237)	2.877 (±0.239)	3.488 (±0.317)	3.731 (±0.381)	2.488 (±0.279)	3.001 (±0.376)
Montipora	3 m	5.108 (±0.692)	3.619 (±0.423)	5.428 (±0.755)	6.975 (±0.862)	7.766 (±0.779)	10.654 (±0.864)
	6 m	3.310 (±0.343)	3.528 (±0.353)	3.7333 (±0.536)	5.094 (±0.654)	7.109 (±0.695)	9.920 (±0.964)

Table 2.6. T-test summary table comparing percentage coral cover between each coral family and depth.

	% mean cover 3 m	% mean cover 6 m	t	df	p
Acroporidae	2.509	2.631	1.778	439.506	0.076
Faviidae	1.235	1.581	6.023	340.21	**<0.0001**
Merulinidae	0.949	1.169	1.584	38.188	0.121
Pocilloporidae	1.376	1.528	2.784	364.315	**0.006**
Poritidae	1.492	1.807	4.887	373.182	**<0.0001**

Table 2.7. T-test summary table comparing the percent coral cover between years for each coral family, depth and reef; showing p-values.

		Acroporidae	Faviidae	Pocilloporidae	Poritidae	Other
Shallow	Ashmore Reef	0.469	0.265	0.493	0.124	0.259
	Cartier Reef	0.548	0.632	0.252	0.460	0.741
	Seringapatam Reef	**0.002**	0.334	0.643	0.333	0.991
Deep	Ashmore Reef	0.841	0.572	0.493	0.821	0.658
	Cartier Reef	0.515	0.917	0.660	0.720	0.871
	Seringapatam Reef	0.912	0.759	0.117	**0.005**	0.523

While mean live coral cover increased at all three reefs, the changes were not large enough to be statistically significant and at current rates would require a further year of coral growth to reach this threshold with the current sampling design. This was also the case at the family level for all locations, with the exception of statistically significant changes in Acroporidae at 3 m (2.309% to 2.697%) and Poritidae at 6 m (1.831% to2.276%) sites on Seringapatam (Table 2.6-2.8, Table A2.1 (Appendix 2.1))

Ashmore, Cartier and Seringapatam Reef temporal changes in coral cover were analysed for Acroporidae, representing the most abundant family, Pocilloporidae, representing the family predominantly affected by bleaching in 2010, and the remaining coral families pooled together. Statistically significant changes over the year were only found at Seringapatam, where Acroporids increased 2.8%, while Pocilloporids declined 1.3%.

Table 2.8. T-test summary table comparing coral cover between years for each coral family and reef; showing mean (±SE) coral cover for each year and p-value from t-test.

	Acroporidae			Other			Pocilloporidae		
Reef	2010 mean	2011 mean	P	2010 mean	2011 mean	p	2010 mean	2011 mean	p
Ashmore	13.475 (n=94)	13.016 (n=93)	0.763	3.541 (n=221)	4.127 (n=252)	0.211	3.263 (n=87)	3.292 (n=81)	0.923
Cartier	14.642 (n=67)	17.184 (n=65)	0.264	3.478 (n=164)	3.489 (n=173)	0.974	3.76 (n=58)	3.924 (n=56)	0.754
Seringapatam	14.497 (n=72)	17.297 (n=72)	**0.032**	4.353 (n=152)	5.295 (n=157)	0.079	5.196 (n=66)	3.917 (n=57)	**0.044**

2.3.2 Bleaching

At all reefs the level of coral bleaching declined markedly from that measured in 2010, accounting for less than 0.2% of the corals (Table 2.10). In the 2011 survey, bleached or partially bleached corals were not seen at Cartier Reef, while a very low number of partially bleached corals were found at Ashmore Reef. Seringapatam sites had the only bleached corals surveyed, but it accounted for less than 0.1% cover.

Table 2.9. Summary table of mean total percent coral cover and percentage of total corals that bleached, partially bleached and unbleached.

		Ashmore Reef		Cartier Reef		Seringapatam Reef	
		2010	2011	2010	2011	2010	2011
3 m	Mean % coral cover (± SE)	24.682 (±2.311)	27.905 (±2.849)	23.485 (±2.358)	24.701 (±2.176)	20.428 (±1.669)	25.098 (±1.251)
	Bleached	0.271	0.000	0.279	0.000	2.390	0.028
	Partial bleached	1.166	0.169	1.146	0.000	1.669	0.000
	Unbleached	98.563	99.831	98.575	100.000	95.941	99.972
6 m	Mean % coral cover (± SE)	26.034 (±2.018)	25.949 (±2.030)	25.722 (±3.168)	30.034 (±3.365)	36.500 (±1.682)	38.791 (±1.936)
	Bleached	0.000	0.000	0.253	0.000	2.387	0.056
	Partial bleached	0.072	0.072	0.704	0.000	1.657	0.113
	Unbleached	99.928	99.928	99.043	100.000	95.956	99.831

Table 2.10. Summary table within each of the most dominant coral families of the relative contribution to bleached percent (partial bleached and total bleached combined) coral cover for each reef and year.

		Ashmore Reef		Cartier Reef		Seringapatam Reef	
		2010	2011	2010	2011	2010	2011
Acroporidae	3 m	3.14%	0.48%	1.94%	0%	10.22%	0.19%
	6 m	0%	0.19%	0.88%	0%	0.3%	0.43%
Faviidae	3 m	2.13%	2.21%	2.27%	0%	20.59%	0%
	6 m	0%	0.78%	2.7%	0%	1.24%	1.12%
Pocilloporidae	3 m	21.67%	0%	24.3%	0%	51.58%	0%
	6 m	0%	0%	19.09%	0%	49.58%	0.73%
Poritidae	3 m	2.36%	0.72%	11.7%	0%	10.8%	0%
	6 m	1.43%	0.45%	4.26%	0%	9.32%	0%

The coral bleaching event in 2010 affected the four most common coral families at all three reefs, but to varying degrees (Table 2.11). The 2011 survey found significant decline in the incidence of bleaching across all these families. Seringapatam was the most affected reef in 2010, with at least 10% of colonies in each of the four major families affected, but approximately 50% of the Pocilloporidae. The bleaching was much less at Ashmore and Cartier in 2010, with most families slightly affected except for Pocilloporidae, where bleaching affected 21-24%. (Table 2.11).The levels of bleaching were greatly reduced at the time of the 2011 survey, to less than 1%, or completely absent, in all families and at all reefs (e.g. Figure 2.18 below).

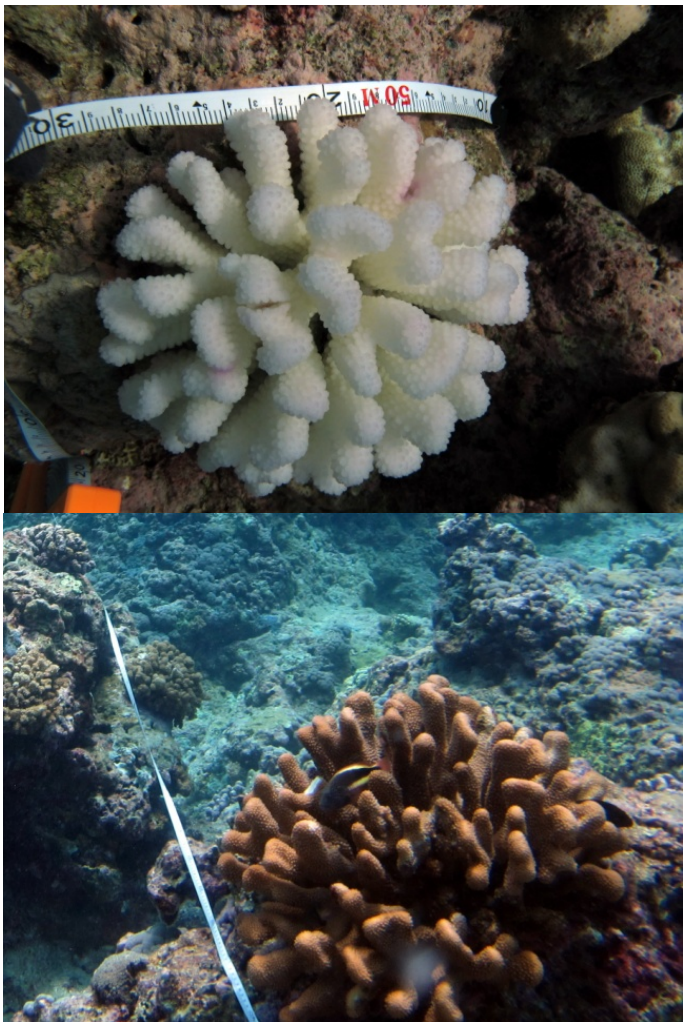

Figure 2.18. Bleached *Pocillopora edouxi* (top photo) was a common site during the 2010 surveys and contributed the bulk of bleached coral within the family Pocilloporidae. In the 2011 surveys almost all colonies of this species appeared healthy (bottom photo). Both images taken at Seringapatam Reef.

Heyward et al. (2010) reported that the bleaching was selective, with some species particularly affected, while others appeared normal. The distribution of significant levels of bleaching in 2010 appeared to be associated more with the distribution of sensitive species than particular depths. This was also true in 2011. In the present survey the very low levels of bleaching observed did not associate in a consistent manner with any particular depth, with shallower (3 m) sites being slightly more affected at Ashmore, the deeper (6 m) sites more affected at Seringapatam and no bleaching at either depth around Cartier Reef (Table 2.9, 2.10).

The most striking visual change on the benthic transects between 2010 and 2011 was the disappearance of bleached corals from the underwater vista. The bright white colonies tended to draw the eye in 2010, but were generally not apparent in 2011. The reductions in bleaching were significant (Table 2.11, Figure 2.19). While the fate of every individual colony cannot be determined and some mortality was probable, it was clear that many colonies bleached in 2010 must have survived. Although growth rates for *P. edouxi* and other bleached species have not been documented on these reefs, it is generally expected that corals of one year old typically achieve colony diameters of 1-5cm. The overwhelming majority of corals on the survey transects appear to be several years old. Figure 2.18 shows a typically strongly bleached *Pocillopora edouxi* at Seringapatam in 2010, with

the second photo indicative of the current healthy appearance of this species. In light of the stable or increasing coral cover over the year, these results are consistent with minimal mortality and general recovery of corals recorded bleaching but alive in 2010.

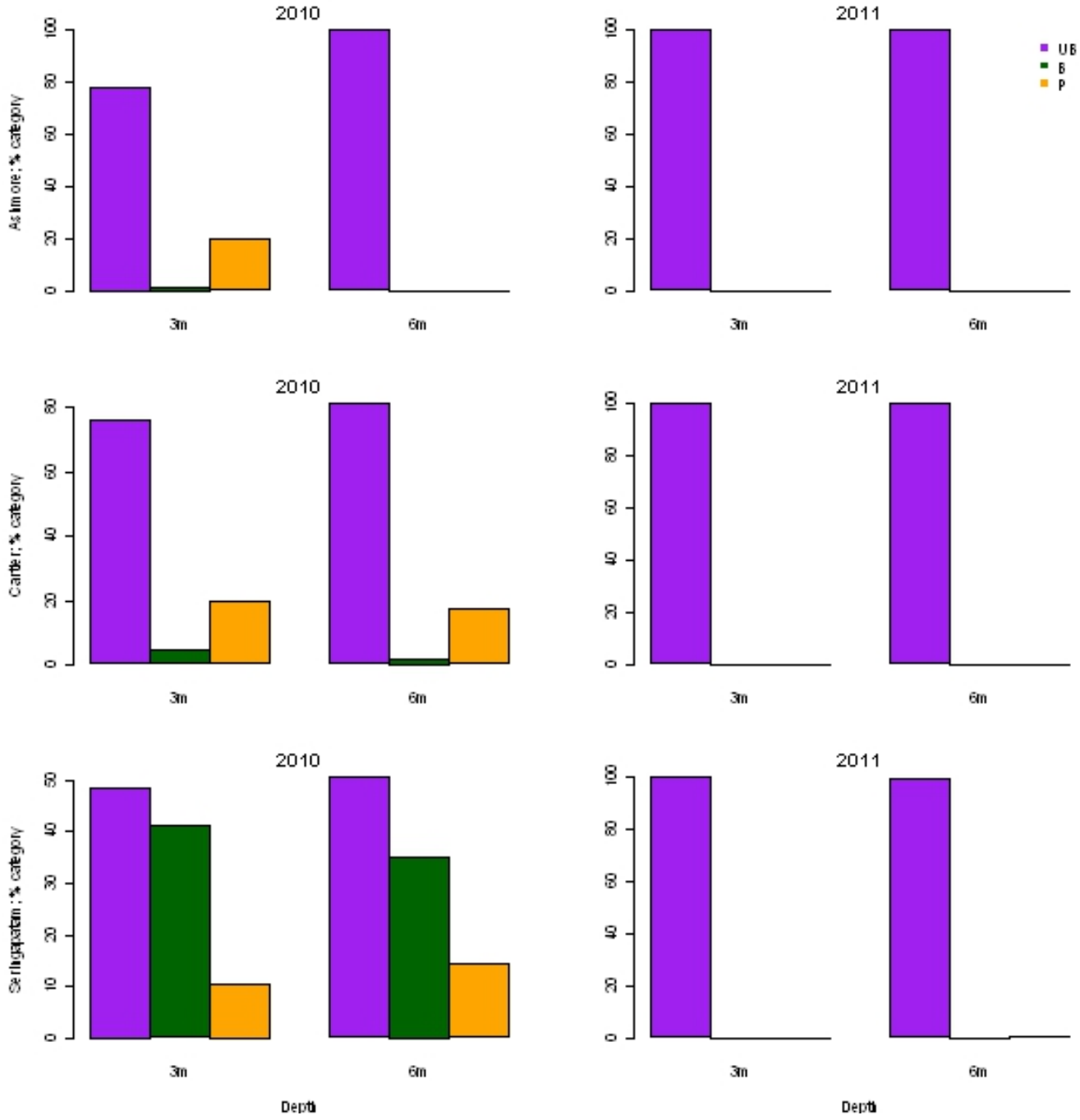

Figure 2.19. Pocilloporidae percentages of coral bleaching categories for each reef, year and depth. Corals were classified as healthy in appearance (UB), partially bleaching (P) or fully bleached (B) during the point intercept analyses.

Table 2.11. Fisher's Exact test summary table comparing the number of coral classified as benthic cover bleached (partial and total bleaching combined) and not bleached between years for each reef, coral family and depth. Showing p-values.

		Ashmore Reef	Cartier Reef	Seringapatam Reef
Acroporidae	3 m	**<0.0001**	**<0.0001**	**<0.0001**
	6 m	0.496	0.037	1
Faviidae	3 m	1	0.232	0.001
	6 m	0.464	0.372	0.794
Pocilloporidae	3 m	**<0.0001**	**<0.0001**	**<0.0001**
	6 m	1	**<0.0001**	**<0.0001**
Poritidae	3 m	0.471	0.0002	**<0.0001**
	6 m	0.358	0.01	**<0.0001**

The changes between years in bleaching is highly significant at all three reefs for Acroporiidae and Pocilloporidae (Table 2.11), but some residual bleaching remains within the Faviidae at all reefs and in the Poritidae at Ashmore, indicating either persistent stress or a new bleaching period for those taxa. A comparison within Faviidae that were bleached at Seringapatam in 2010 and 2011 found that in both years a number of favid species were bleached, but that the genera *Cyphastrea* and *Echinopora* were in common. This may reflect the general sensitivity of these groups.

Figures 2.20-2.22 provide pairwise comparisons of annual changes in the abundance of Acroporids, Pocilloporids and other hard coral families for each location. While it is clear that the direction of changes in these coral groups varied at different locations around each reef, the overall trend is a positive increment in live coral cover. The most notable exception is a mean loss of Pocilloporids at Seringapatam. This may relate to the prevalence of bleaching measured there in 2010 (Heyward et al. 2010). While there is no doubt many Pocilloporids survived the bleaching at Seringapatam, the data suggest that the impact was more severe there than at Ashmore or Cartier Reefs.

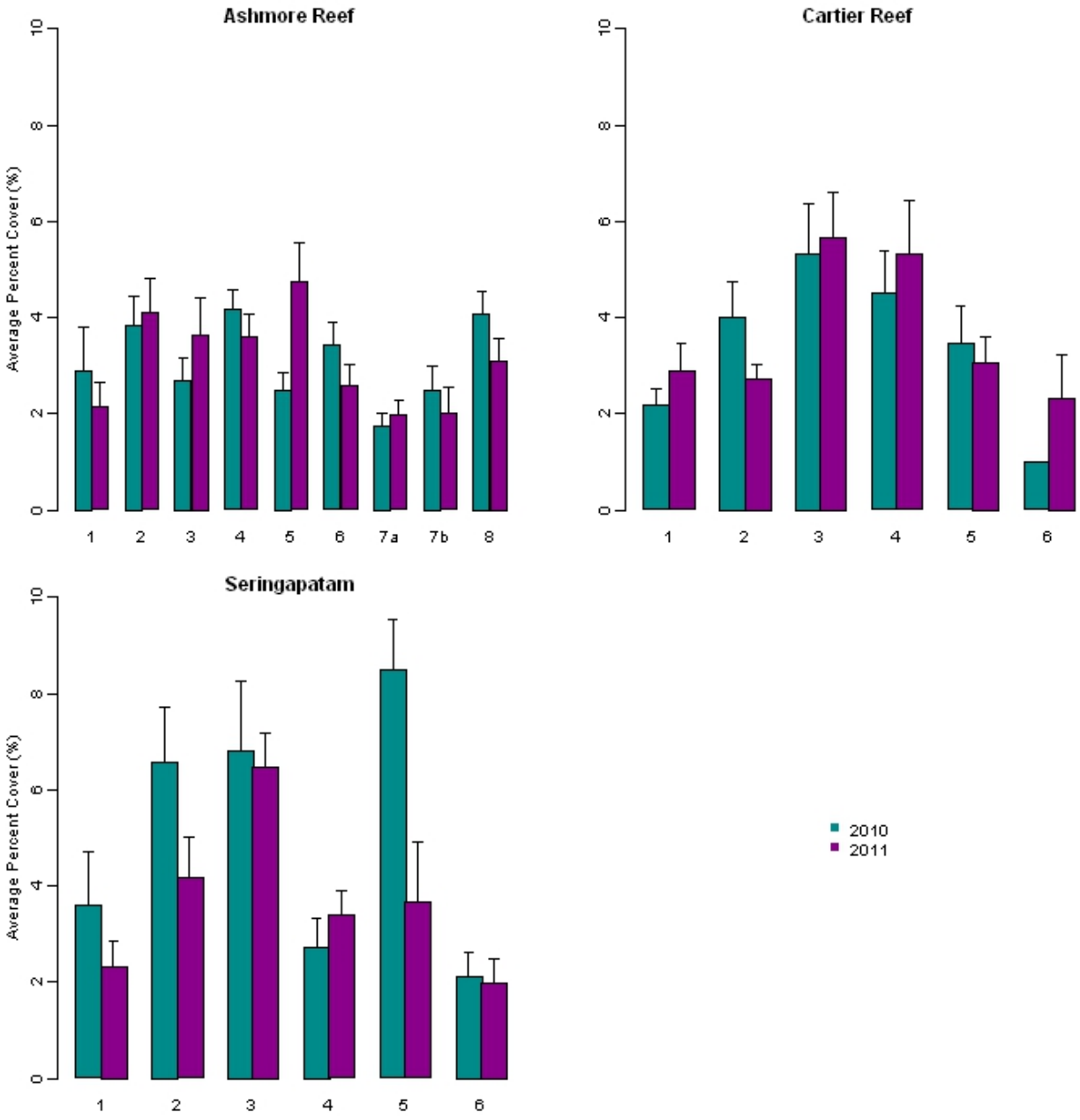

Figure 2.20. Annual change in mean (+SE) percent Pocilloporidae cover per location an Ashmore, Cartier and Seringapatam Reef between 2010 and 2011.

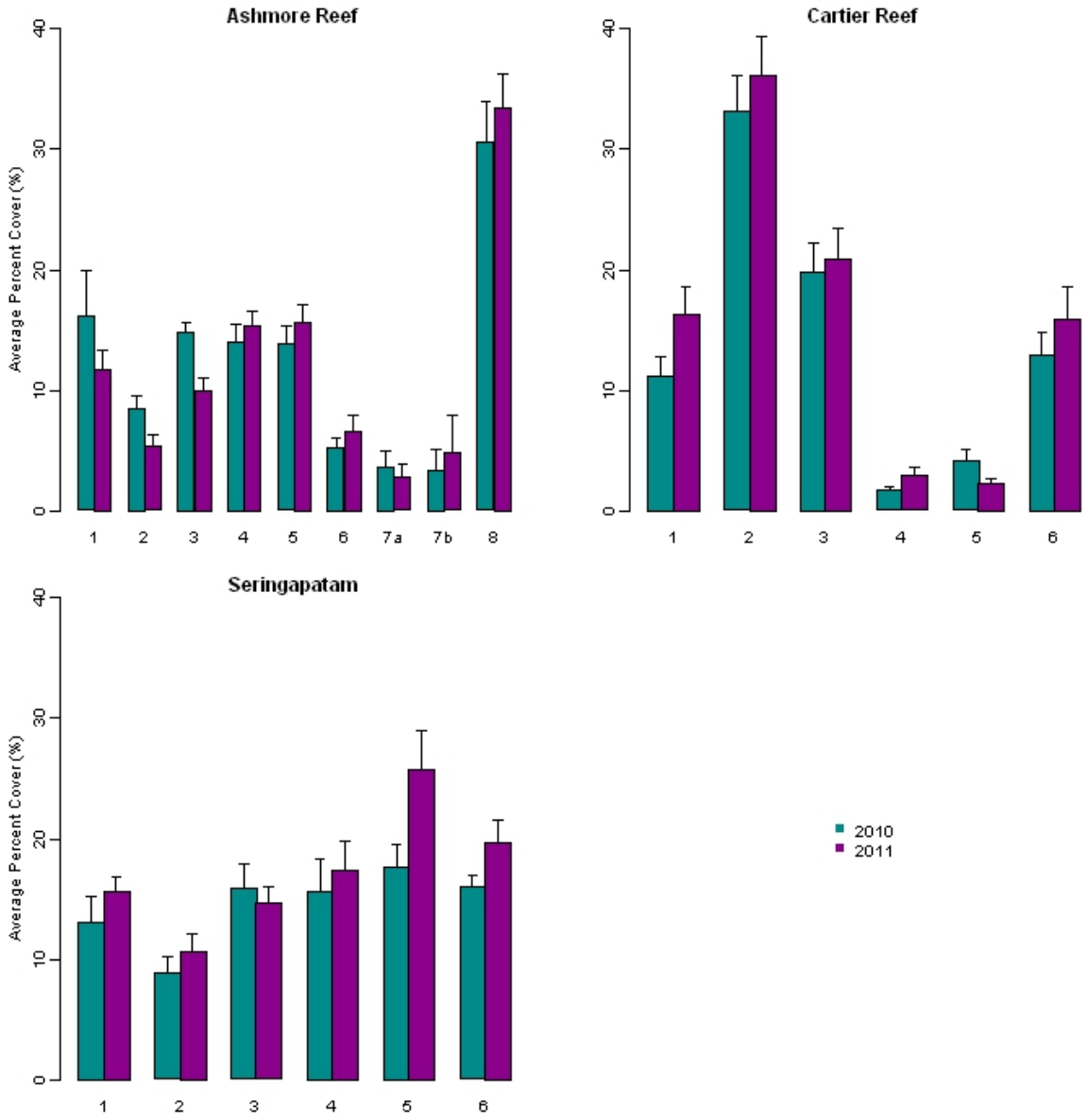

Figure 2.21. Mean (+SE) percent Acroporidae cover in Ashmore, Cartier and Seringapatam Reef in 2010 and 2011.

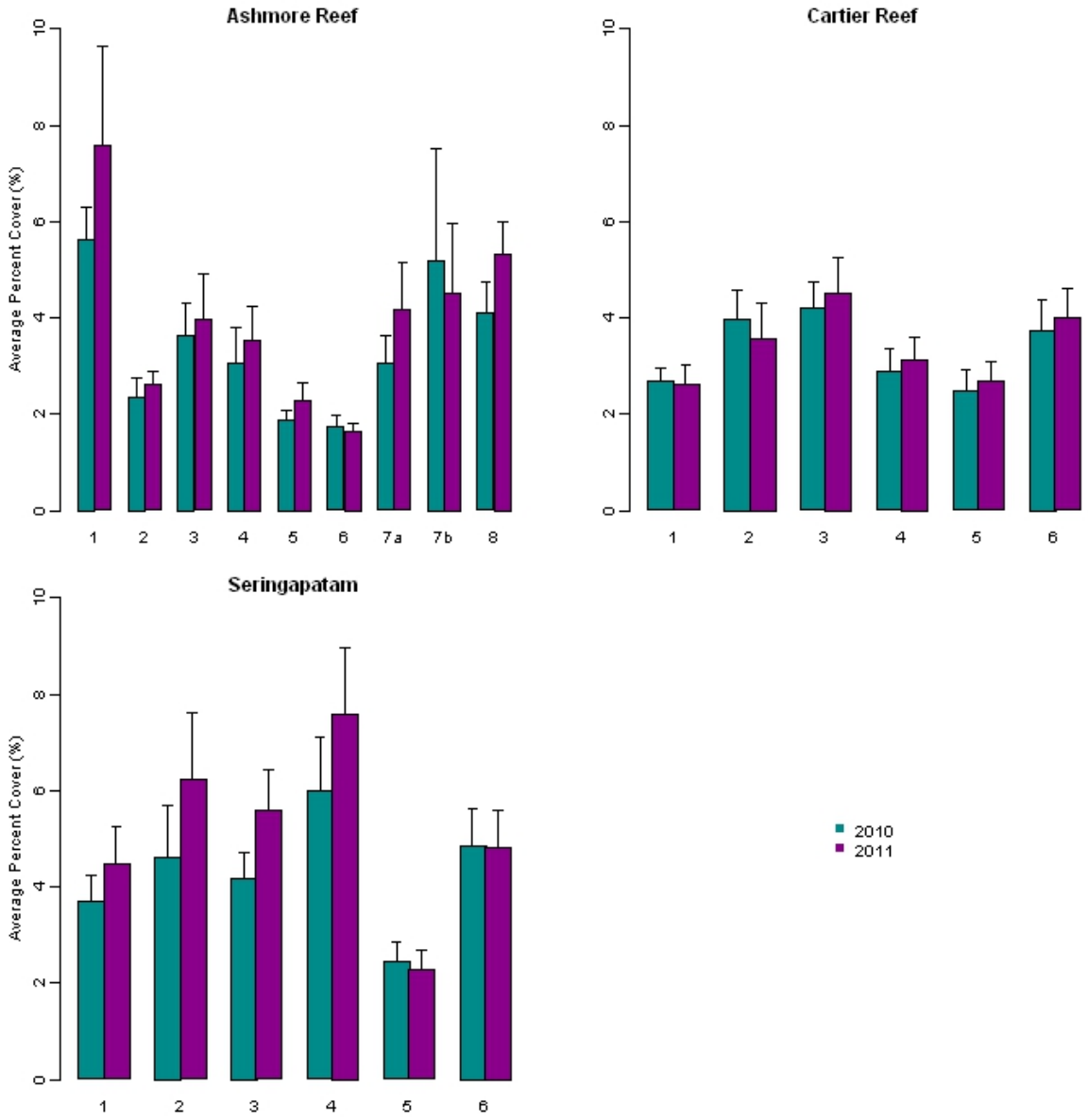

Figure 2.22. Mean (+SE) percent Other (includes Faviidae, Merulinidae, Poritidae and Other) family groups coral cover at Ashmore, Cartier and Seringapatam Reef in 2010 and 2011.

2.4 Discussion on reef benthos

Overall composition of the shallow reef benthos at Ashmore, Cartier and Seringapatam Reefs has remained consistent between 2010 and 2011, with live hard coral and turf algae the dominant groups. Average live coral cover is increasing at all reefs, at a similar modest rate, although with some variability between locations within each reef. The mean positive change in hard coral abundance at reef level, of 2.7%, is a medium rate of change compared to reports from other reefs but is not a statistically significant change. At Scott Reef, annual monitoring using similar methods between 1994-97 (Heyward et al. 1998) found a very similar rate of annual increase in coral cover to the present study, but during the same period, reefs at equivalent latitude on the Great Barrier Reef, (GBR) increased at approximately 5% p.a. This latter rate was also inferred in a recent study of Ashmore, where the abundance of coral was compared from surveys in 2005 and 2009. The differences in rates of increase between the present study may relate to differences in methodology, but may have been influenced by selection of several different sites. The present study has locations with both higher and lower mean coral cover than that reported by (Ceccarelli et al. 2011). The effect of location on benthic assemblages in significant on these reefs and we found that even within locations both depth and transect level variations in coral composition and abundance could be important. Within reefs, location had a significant effect on both, although positive or negative changes in live coral between years were not consistent with regard to any particular aspect on each reef.

The greater coral increment rates reported for Ashmore Reef between 2005-9, capture a period where coral cover was originally low (10% cover), as was the case for GBR reefs such as Carter, Non Name and Yonge, which saw even faster rates of coral cover increase in the period 1994-97, following earlier catastrophic losses from crown-of-thorns starfish outbreaks. In the current study, notwithstanding caution in relation to spatial variations between the studies, coral cover was already moderate and interactions between benthic organisms may be having a greater effect on coral growth. In addition, the 2010 bleaching event, although moderate in terms of the overall coral community affected, is likely to have cost many corals energy. As such, the subsequent year may reflect a lower than average period of coral growth. With the current repeated measures sampling design, another year of similar coral growth would produce a statistically significant increase at the 95% confidence level.

The coral bleaching observed in 2010 was largely absent in 2011, with only residual occurrences associated with individual coral colonies. The two coral families most affected by bleaching in 2010, Acroporidae and Pocilloporidae, showed a significant change in their bleached status, with most colonies now displaying normal pigmentation. The presence of numerous adult sized colonies of species that were originally widely bleached, suggests that many corals observed as bleached in 2010 have survived. At Seringapatam, where Pocilloporid species were most strongly affected by the 2010 bleaching, changes at each of the size monitoring locations showed the majority had experienced a decline in the abundance of this family. However, there was no clear correlation between the level of bleaching measured in this family at each location in 2010 and the amount of coral loss recorded in 2011. Overall, it would seem likely that the duration and intensity of bleaching stress at Seringapatam in 2010 was greater than experienced at Ashmore or Cartier Reefs, with subsequently greater loss of the more sensitive species at Seringapatam.

At the whole reef scale, the benthic community structure and patterns of temporal change from 2010-11 were very similar between the three reefs. There is no evidence of broadscale disturbance that correlates with the presence of an uncontrolled release closer to Ashmore and Cartier reefs than to Seringapatam. The rates of change in live coral are slower than would have been predicted from the most recent previous studies, but in keeping with older reports from other undisturbed

reefs in the region. Unless these reefs face further disturbance, through cyclones, bleaching or pollution, the current monitoring design should confirm significant coral growth continuing in the next few years. The composition of the coral communities will influence the rates of incremental coral growth. It is likely that some of the variability between locations within and between reefs will become more exaggerated over time, with coral communities dominated by genus *Acropora* anticipated to outperform those with a more mixed assemblage.

2.5 References

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Appendix 2.1

Table A2.1. ANOVA summary table comparing percent coral cover by main effects and interactions – reef, coral families (Acroporidae, Pocilloporidae and Other) and year.

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Coral families	2	41889	20944.300	539.156	**<0.0001**
Year	1	145	144.600	3.722	0.054
Reef	2	710	354.800	9.133	**<0.0001**
Coral families × Year	2	162	81.100	2.088	0.124
Coral families × Reef	4	518	129.500	3.334	**0.010**
Year × Reef	2	41	20.300	0.523	0.593
Coral families × Year × Reef	4	310	77.600	1.998	0.092
Residuals	1969	76489	38.800		

3. CORAL REPRODUCTIVE ACTIVITY

3.1 Introduction/Background on 2010 observations

Reef building corals most commonly reproduce through the production of planktonic larvae, either brooded following internal fertilisation then released, or developed in the plankton following broadcast spawning of gametes (Harrison and Wallace, 1990). Both brooding and broadcast spawning species can form important components of coral communities, but the majority of species appear to utilise broadcast spawning and reproduce during specific times of year (Babcock et al. 1986), Along the North-west Australian coast, the peak broadcast spawning season is in autumn (Simpson, 1985); although a spring spawning event involving fewer species is reported from a number of NW Australian reefs (Gilmour et al. 2009; Baird et al. 2011).

Veron (cited p58 in Russell & Hanley, 1993) listed 256 scleractinian coral species from Ashmore Reef, with at least 186 species noted in more recent surveys (Ceccarelli et al. 2011). A majority of those species would be expected to reproduce by broadcast spawning gametes in brief seasonal or annual events. Coral reproduction has not previously been studied in any detail at Ashmore, Cartier or Seringapatam Reefs. Inferences to predict spawning times have relied on data from studies at Scott Reef (see Gilmour et al. 2009), observations more broadly along the NW Shelf (Heyward, pers. obs.) and reports of coral spawning in Singapore (Guest et al. 2005). Based on regional patterns it was expected that some spawning would occur in early March 2010 and also in the first week of April 2010 after the preceding full moon, which occurred on 30th March 2010. The 2010 Montara reefs survey (Heyward et al. 2010) included sampling at Ashmore to detect mature corals likely to spawn.

If colonies with mature gonads were found, a highly probable spawning period was predicted for the nights of 6th-8th April, 2010. The schedule of the research cruise meant that any spawning in March 2010 would have been missed, but that there would be a window of a few days after arriving at Ashmore Reef in which to detect mature coral colonies ahead of a potential April 2010 spawning window. Coral reproduction was investigated immediately upon arrival at Ashmore Reef, on 4th April 2010, by sampling a broad range of common species during site surveys and assessment of fresh cross sections for the presence of mature gonads. Most corals showed no visible sign of mature gonad in freshly broken cross sections, which is the common method used for rapid assessment of reproductive status (Heyward, 1986; Baird et al. 2002). A few species, mainly brain corals in the genera *Goniastrea*, *Favites* and *Favia*, contained remnant amounts of mature gonad, suggesting a split spawning in 2010, with the majority of gonad released in March. A collection of one favid, *Favites adbdita*, maintained alive on board RV Solander, was observed to spawn within the predicted window on the nights of 6th-7th April. The gametes were collected, cross-fertilised and the resulting larvae cultured through to settlement. However, a question mark remained about possible effects of the Montara uncontrolled release on coral spawning in the majority of coral species at these reefs, given the potential for oil, at least in chronic pollution scenarios (Loya & Rickevich, 1980), to damage the reproductive system of corals. Despite the apparent normality of the observed spawning, high levels of fertilisation and subsequent normal development for one coral species in 2010, the inability to confirm if the majority of coral species were participating in normal reproductive activity prompted a more comprehensive and temporally extensive set of studies on this aspect of coral health during the 2011 surveys.

3.2 Methods

3.2.1 Field sampling

The assessment of coral reproductive activity used three measures of coral reproductive health and successful propagation of new corals. These included analysis of fecundity and gonad size from collected samples of the existing adult stock, assessment of newly settled corals on deployed terracotta tiles, and counts of 1-3 year old juveniles on the benthic survey transects. Each of these methods provides insight into coral reproductive activity at a different stage in the life cycle. The sampling was integrated into the broader benthos survey design, using all or some of the locations visited in the 2011 survey (Figures 3.1-3.3).

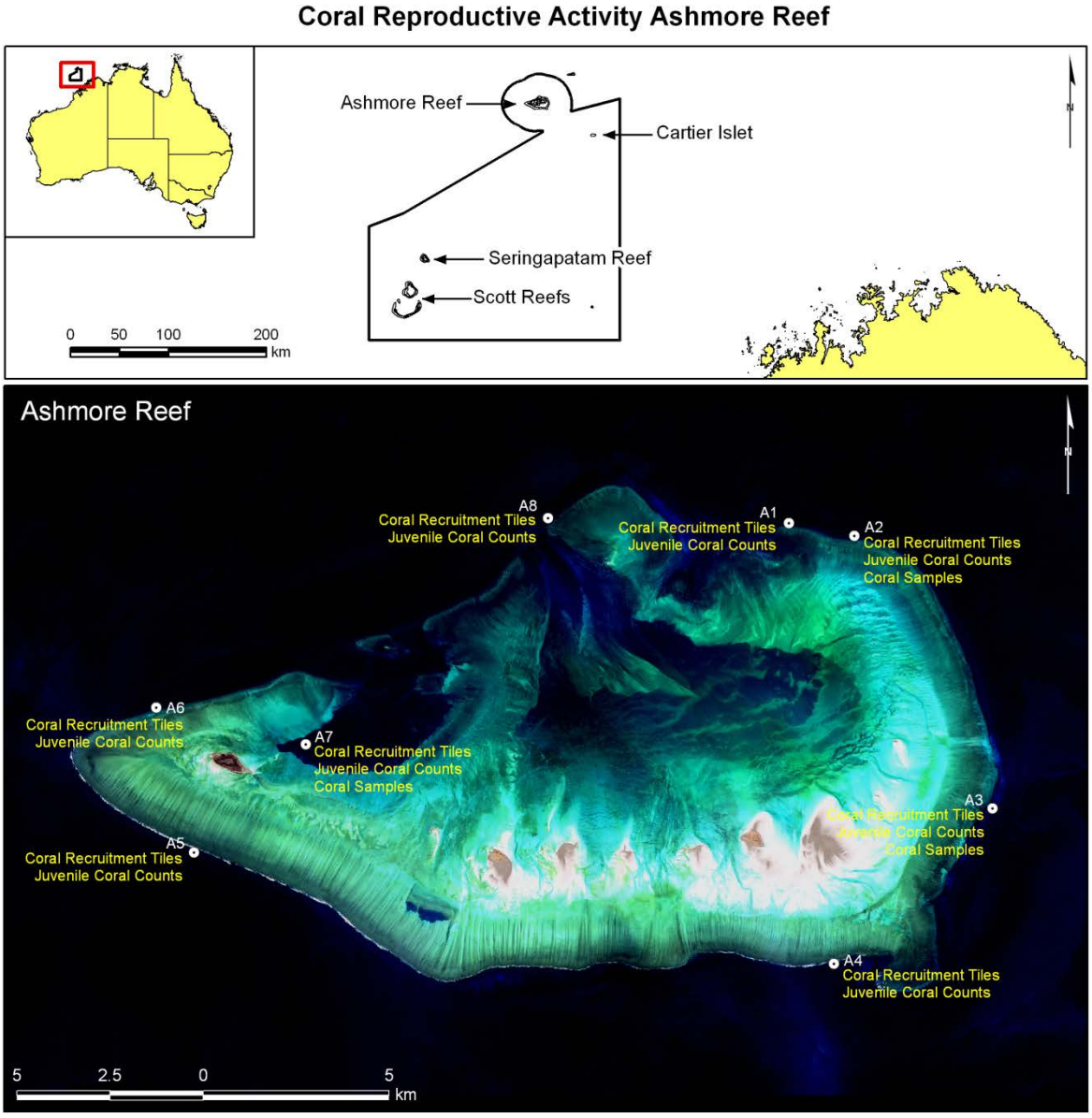


Figure 3.1. Ashmore Reef - Major sampling locations for studies of coral reproductive activity were located on or nearby the primary benthic monitoring locations (A1-A8). Three types of sampling were used. Samples for analysis of gonad condition were collected from a subset of locations.

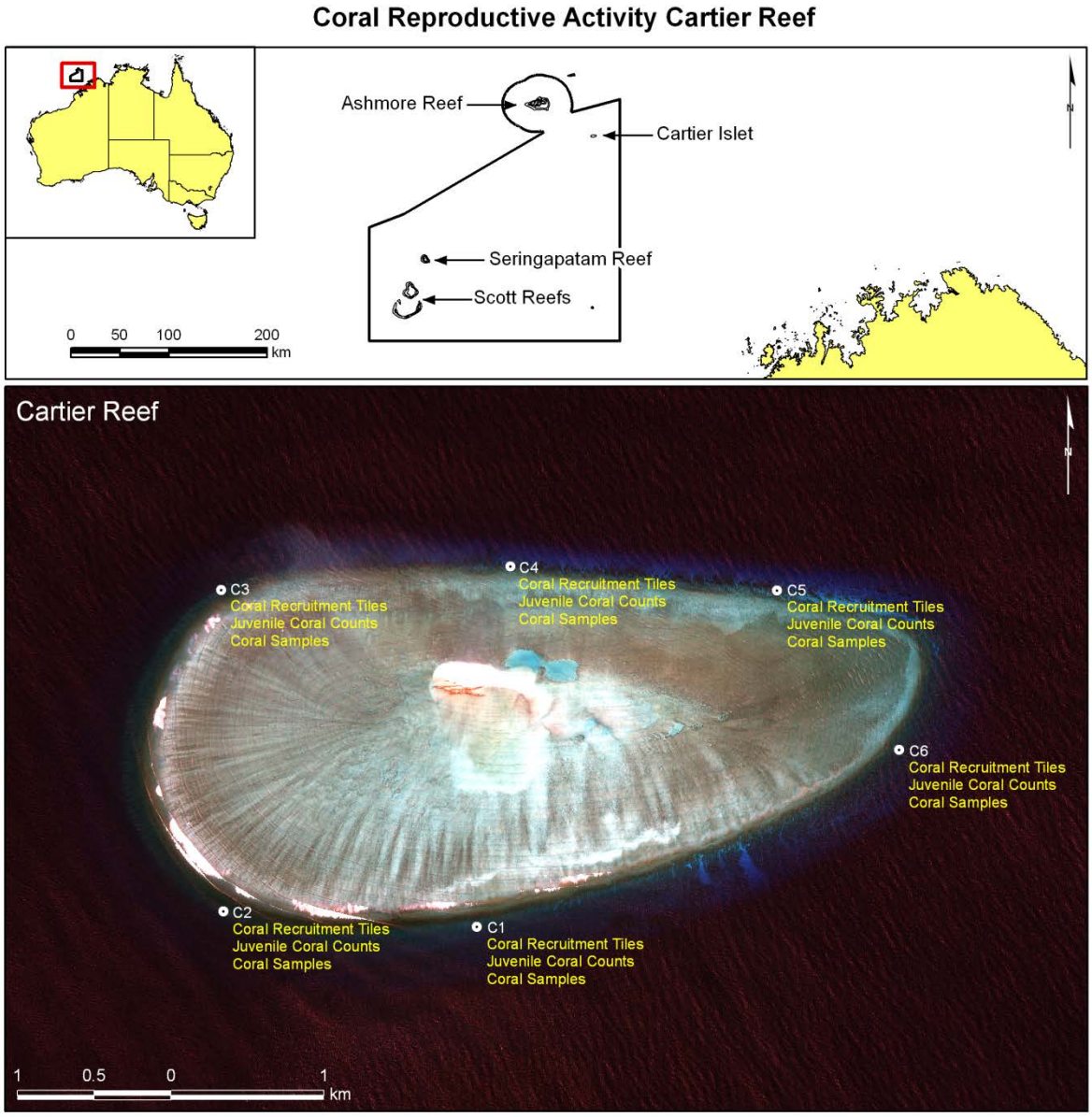


Figure 3.2. Cartier Reef - Major sampling locations for studies of coral reproductive activity were located on or nearby the primary benthic monitoring locations (C1-C6).

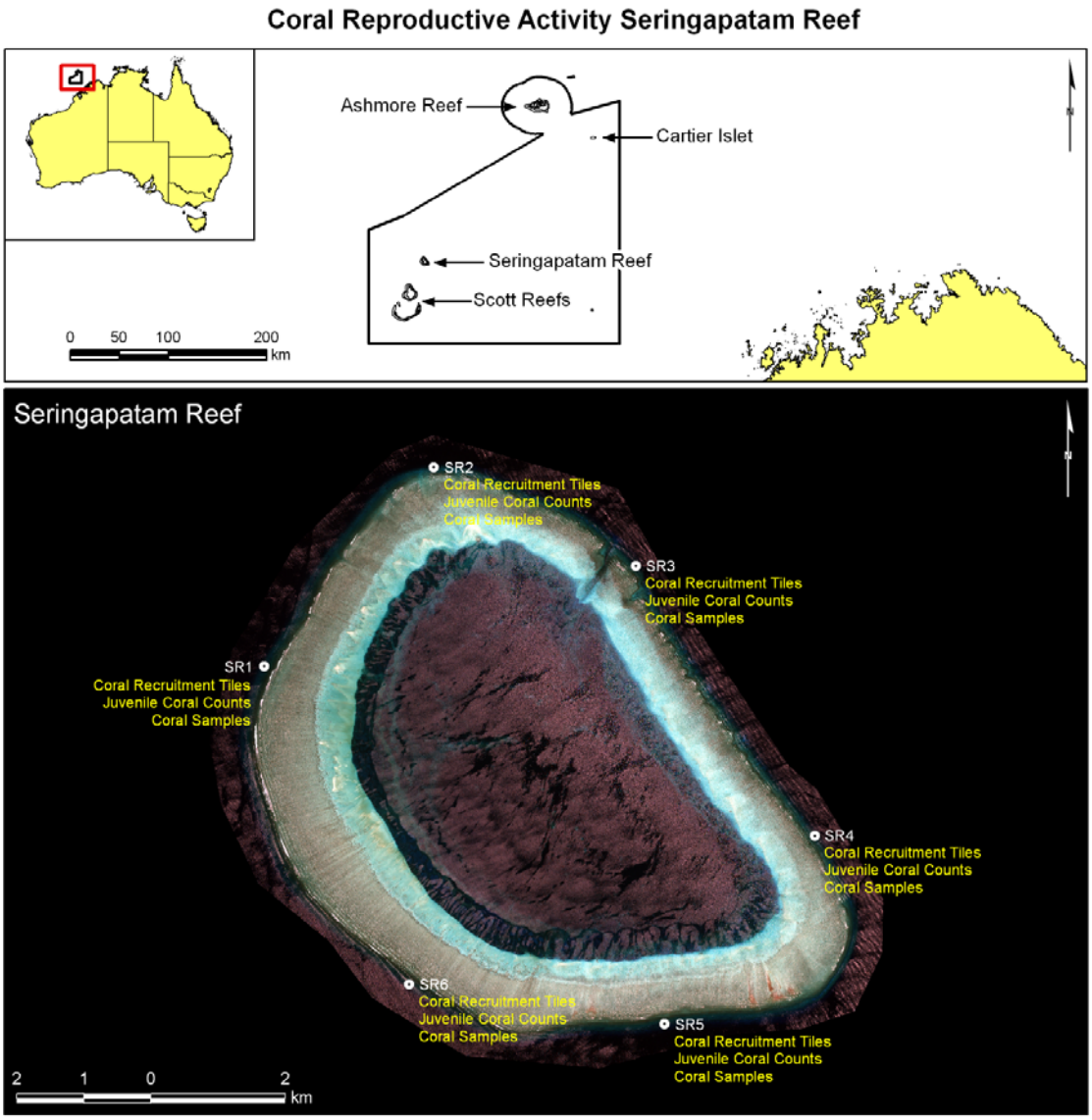


Figure 3.3. Seringapatam Reef - Major sampling locations for studies of coral reproductive activity were located on or nearby the primary benthic monitoring locations (SR1-SR6).

3.2.2 Coral gamete assessment

In February/March 2011, prior to the predicted autumn spawning, replicate samples were collected from species of spawning and brooding corals across all three reefs. At Ashmore, Cartier and Seringapatam Reefs, divers visited multiple reef locations and collected a representative sub-sample of corals (see Figures 3.1-3.6). Live coral fragments were removed by hand from the reef with hammer and chisel, and then processed on board the RV Solander. Samples were collected at Ashmore Reef from the 25th February to the 4th of March, Cartier Reef from the 4th to the 7th March and Seringapatam from the 8th to the 10th March. The live pieces were visually assessed for the presence or absence of gonad and voucher samples then preserved. Initial fixation was in 10% formalin-seawater for a minimum of 24 hours, then samples were transferred into 70% ethanol and shipped to the AIMS Perth laboratory In total, 515 samples, representing 56 species, were collected and preserved onboard the RV Solander.

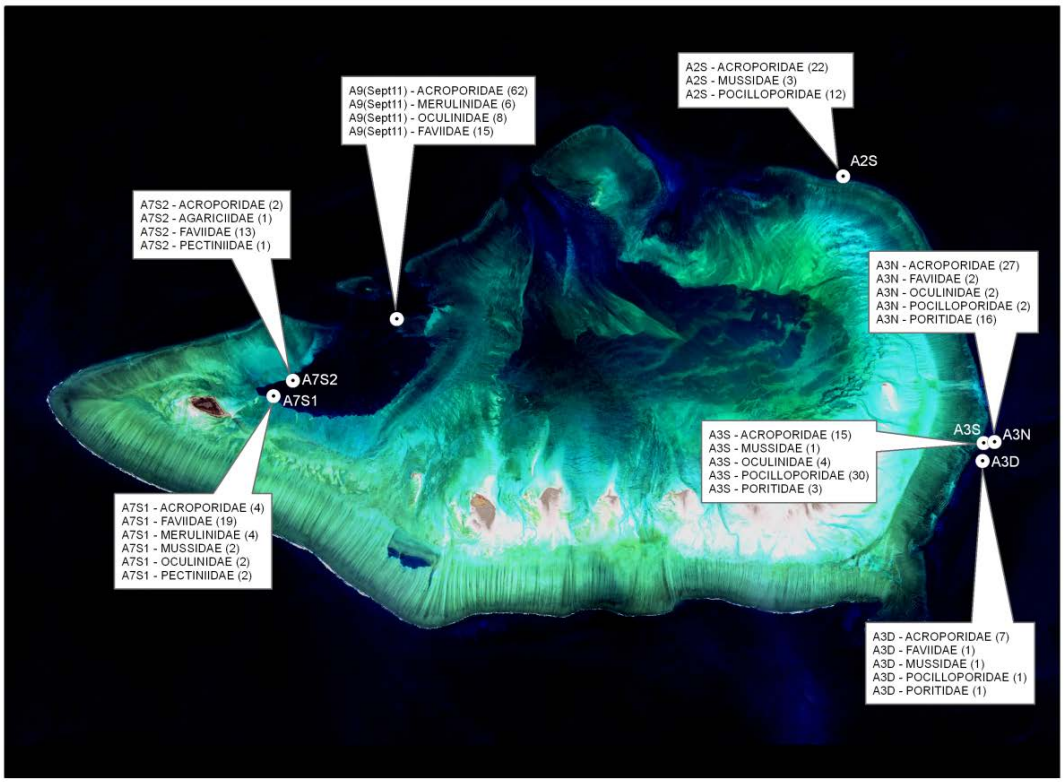


Figure 3.4. Ashmore Reef – coral reproduction sampling locations. Information in each white box shows the number of samples collected within each coral family. All sampling in February-March, 2011, except site A9 which refers to the September sample.

3.2.3 Secondary Sampling

A secondary survey of coral gonad condition was conducted on Ashmore Reef on the 11th-12th September 2011, prior to the possible spring spawning event. Corals were surveyed at two sites that were not previously sampled during the autumn survey. The majority of the species collected were Acroporiids and Faviids. The same process of decalcification and dissection was carried out as per the prior samples to confirm whether or not these species spawn in the spring as well as the autumn and to compare the fecundity and egg size between seasons. Many of these additional samples were also scored in the field. Visible eggs were given a ranking from 1-4 based on the colour and size as per Harrison et al. (1984) and Guest et al. (2005).

- Score 1 – Large pigmented (red or pink) eggs were clearly visible within polyps, indicating that colonies will participate in the next spawning event within a month;
- Score 2 – Large unpigmented (white or cream) eggs were clearly visible within polyps, indicating colonies will spawn following within two months;
- Score 3 – Small unpigmented (white or cream) eggs were visible within polyps, indicating colonies were unlikely to spawn for several months;
- Score 4 – No eggs were visible within polyps, indicating that polyps had recently spawned, or will not spawn for many months.

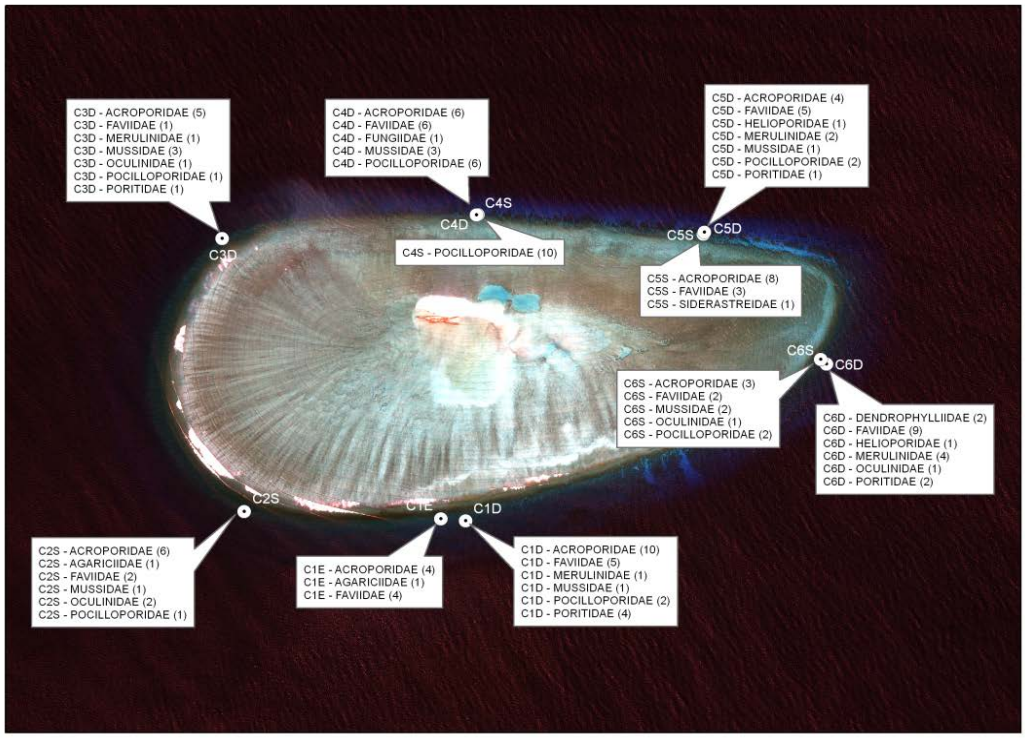


Figure 3.5. Cartier Reef – coral reproduction sampling locations. Information in each white box shows the number of samples collected within each taxonomic coral family.

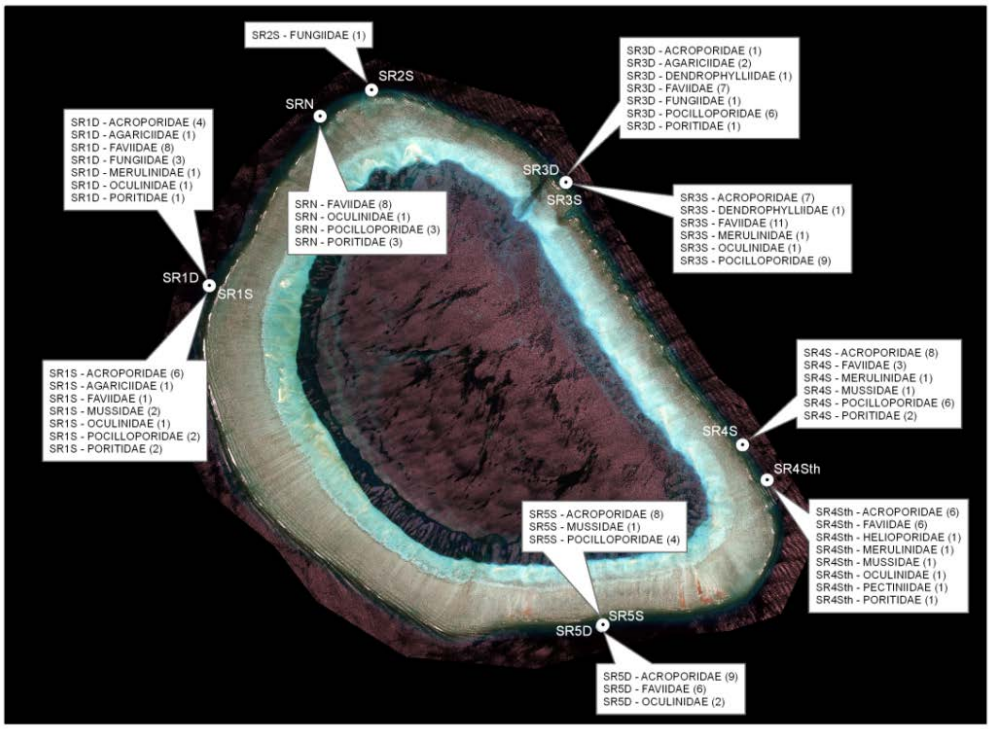


Figure 3.6. Seringapatam Reef – coral reproduction sampling locations. Information in each white box shows the number of samples collected within each taxonomic coral family.

3.2.4 Statistical analyses.

The coral egg size and count were summarised through bar charts, showing the mean (+SE) egg size and count for each species and reef. The difference in egg counts and mean egg size for a subset of coral species within and between reefs were compared using analysis of variance (ANOVA) (Zar 2010). Only species with greater than two samples at all sites were analysed. These species were: *A. digitifera, A. gemmifera, A. millepora, A. palifera, A. polystoma, A. specifera, Montipora sp, Cyphastrea microphthalma, Echinopora lamellosa, Goniastrea edwardsii, Goniastrea pectinata, Goniastrea retiformis, Symphillia recta, A. tenuis, Merulina ampliata, Platygyra sinensis* and *Galaxea fascicularis.* All data was transformed using Logarithm +1. All analysis was conducted using the statistical package R {R Development Core Team, 2011}.

Laboratory assessment

In the laboratory, samples were decalcified and examined using a microscope to count and measure visible eggs and to determine the stages of development of gametes.

Decalcification

Coral samples were decalcified individually in plastic cups in a fume hood. A small piece of coral sample was placed into the bottom of each plastic cup and completely covered in 10% formic acid. Every morning the acid was drained off into a waste container and the cup was re-filled. The amount of acid changes varied, with some corals completely decalcified within 1-2 days and others needing about a week. Following decalcification, coral tissues were stored in 70% ethanol.

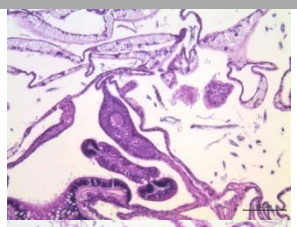
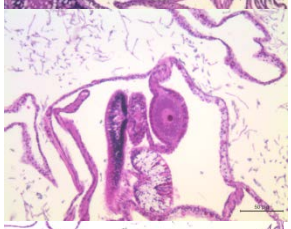
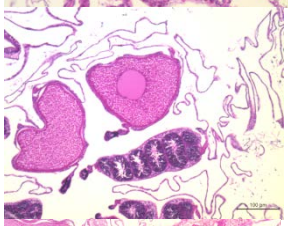
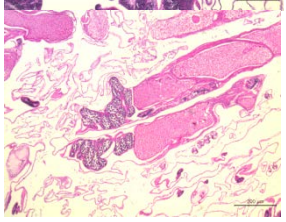
Egg size and fecundity

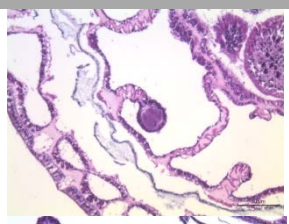
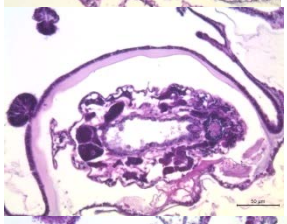
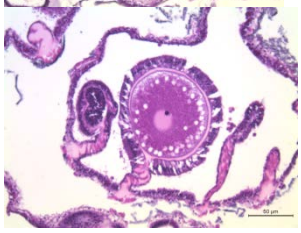
Decalcified tissue samples were used to estimate the number and size of eggs within polyps. Polyps usually have a high level of synchronicity within the colony so a small sample is sufficient for determining the overall reproductive condition and gamete maturity (Baird et al. 2011). Six polyps were dissected from each colony. The polyps were chosen from the middle of each section to avoid the growing tips of the branch. Exact egg counts of each of the six polyps were done for the dissected Acroporid species and all eggs from each of the six polyps were measured. For all other species a sub-set of ten eggs were measured from each polyp. The egg counts per polyp were estimated by counting the number of eggs in a mesentery and multiplying by the number of mesenteries per polyp. The only exception was the Mussidae species which do not have distinct polyps. For each of these samples, six similar sized sections were examined from a single valley. Exact counts were observed for each of the six sections.

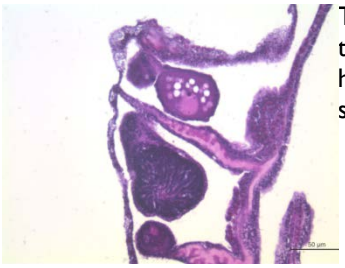
Coral eggs were measured under a Leica M205C stereo microscope; maximal and medial diameters were measured using Leica Application Suite version 3.8 software. The geometric mean for each oocyte was calculated as the square root of the maximal x medial diameter (Wallace 1988).

Histology

Tissue samples were examined using histological techniques for a sub-sample of 359 corals. The decalcified tissues were dehydrated through graded ethanol, cleared in chloroform and embedded in paraffin wax. Samples were sectioned at 6 microns, mounted on slides and stained in Harris' Haematoxylin and Young's Eosin. Using a Leica DMLB compound microscope, the stages of development for eggs and sperm were ranked Stage I to Stage IV according to the guidelines of Szmant-Froelich et al. (1985) and Vargas-Angel et al. (2006). Figure 3.7 provides examples for a selection of coral families of the histology staging applied.

Stage	Acroporidae female gametes (*A. Gemmifera*)	Egg Size (µm)		Acroporidae male gametes (*A. Gemmifera*)
I	Small, oblong shaped oocyte developed within the mesogleas.	20-50		Clusters of unbound cells. Stained purple to blue.
II	Similar to Stage I but larger. Still within the mesoglea. Cytoplasm present.	50-200		Spermaries with clusters of spermatocytes within the mesoglea. Nuclei stained blue and lining the periphery.
III	Size increases dramatically. Yolk is granular and lipid vesicles appear. Nucleus is round and near the centre.	200-600		Spermaries lined together. Spermatocytes migrated to the periphery of the spermary forming a distinct lumen in the centre.
IV	Nucleus migrates to the periphery of the oocyte, may become grooved or saddle-shaped. Oocyte shape may also become irregular.	>300		Mature spermatocytes with tails loosely packed within the testes. Tails are stained light pink and are all pointing in a roughly uniform direction.

Stage	Pocilloporidae female gametes (*Pocillopora damicornis*)	Egg Size (µm)		Pocilloporidae male gametes (*Pocillopora damicornis*)
I	Small oocyte within the mesoglea. May be multiple oocytes in a single ovary.	<20		Clusters of cells surrounded by a spermatogonial wall. Stained dark blue.
II	Similar to Stage I but slightly larger. Cytoplasm present.	20-30		Similar to Stage I. Spermatocytes were more densely packed and evenly distributed throughout the spermaries.
III	Oocyte is much larger. Nucleus is in the centre. Cytoplasm vacuoles are visible.	50-100		Oval or tear shaped testes. Spermatocytes have migrated to the periphery to form a lumen in the centre.

IV	Oocyte may be surrounded by a dark membrane. Nucleus shifted towards the periphery. Cytoplasmic vacuoles enlarged.	>50		Testes are loosely packed throughout. Spermatocytes have tails, all pointing in the same direction.

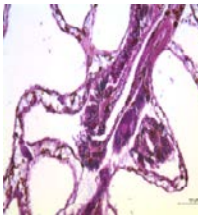
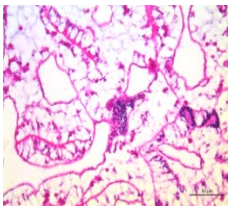
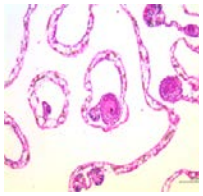
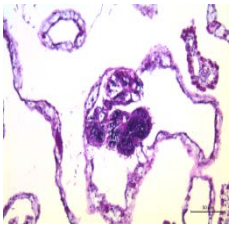
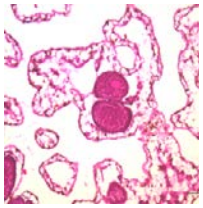
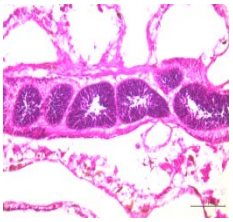
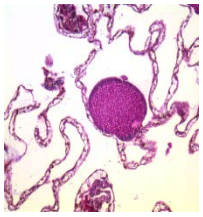
Stage	*Porites* female gametes		Egg Size (µm)	*Porites* male gametes	
I	Oocytes in the mesoglea. Small oval shaped cells stained deep red to purple with a large nucleus, stained pink. Nucleolus dark red.		10-50	Small clusters of cells near or within the mesoglea. Stain dark purple.	
II	Oocytes enveloped in mesoglea and surrounded by a layer of cytoplasm. Nuclei are in the centre. Nucleus stained soft pink and oocyte stained bright pink.		50-100	Testes completely surrounded by mesoglea. Clusters of spermatocytes with large nuclei and a distinct boundary.	
III	Yolk cells and lipid granules accumulating. Round, oval or irregularly shaped. Nucleus may be in the centre or moving toward the periphery.		100-200	Testes are oval, tear shaped or irregular. Spermatocytes migrated to the periphery to form a lumen in the centre. Nuclei stained dark pink or magenta. Tails observed, light pink.	
IV	Large irregularly shaped oocyte. The nucleus migrated to the periphery.		>150	Not observed.	

Figure 3.7. Criteria and examples for classification of gametocytes in *Acropora spp.*, *Pocillopora spp.* and *Porites spp* from histological samples collected from Ashmore, Cartier and Seringapatam reefs in north Western Australia in Feb-Mar 2011.

Coral recruitment

Terracotta tiles were deployed to estimate coral recruitment rates at Ashmore Reef and Cartier Islet, the main control reef, Seringapatam, and the secondary control reef, Scott Reef. The exact peak of spawning activity was unknown, but based on the timing at other locations in the region (Gilmour et al. 2009) was likely to occur following full moons falling on the 18th February and 20th March, 2011. In order to capture recruits from both possible autumn mass spawning windows, the recruitment tiles were deployed between 11th February 2011 and 17th February 2011, approximately two weeks prior to the first predicted autumn mass spawning window, and collected twelve weeks later (± 5 days).

Tiles were attached to the reef (Figure 3.8), along the first 100 m at each of the previously established 6 m depth benthic monitoring locations (see Figures 3.1-3.3). This provided samples of recruitment from 8 locations at Ashmore Reef, six locations at both Cartier and Seringapatam, and five locations at Scott Reef. The terracotta tiles (110mm x 110mm x 10mm) were deployed at each location in three groups of six tiles separated by 50 m on the reef slope (18 tiles location^{-1}). Each of the six tile groups were spaced haphazardly, approximately 1 m apart, and attached to the reef via a central 316 stainless bolt holding the tile onto a stainless steel mounting plate attached to the reef using masonry plugs as per Mundy (2000). Total deployment was 450 tiles. Divers collected the deployed tiles by hand in May, taking care to separate individual tiles using plastic spacers, to protect recruits settled on the surface. The retrieved tiles were bleached, transported to the AIMS laboratory in Perth and the coral recruits identified to one of four taxonomic groups (Family Acroporidae, Pocilloporidae, Poritidae or Others) according to Babcock (2003), using a dissecting microscope.

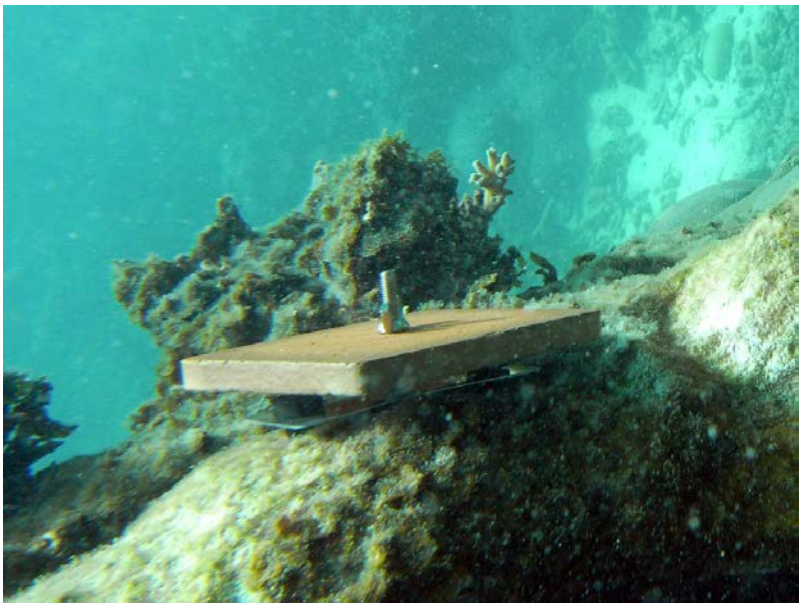


Figure 3.8. Coral recruitment tile *in situ* on the reef: A newly deployed tile will develop natural biofilms over coming weeks or months ahead of the spawning and recruitment period. These films provide important chemical cues for settling larvae, hence deployment several weeks in advance of predicted spawning is desirable. Divers can retrieve the tile by hand using the wing nut, while the base plate can be left attached to the reef, allowing precise location of future tile deployments.

Juvenile counts

Juvenile corals were surveyed visually by divers at all locations at Ashmore, Cartier, and the main control reef Seringapatam in April 2010 and between February and May 2011. In addition, two sites at Scott Reef (SL1 and SL2) were surveyed in 2010. Belt transects 5 m long and 34 cm wide were surveyed for juvenile corals at the start of each of the 6 m benthic monitoring transects at both 3 m and 6 m depths for all sites; a total of 96 transects at Ashmore and 72 transects at each of Cartier and Seringapatam reefs per year (see sampling design Figures 3.1-3.3). The belt width, 34 cm, was the width of an A4-sized plastic slate, used for regular *in situ* calibration. All corals ≤5 cm were identified *in situ* to Genus or Family level and measured to the nearest centimetre according to the AIMS Standard Operational Procedure 10/2008 for benthic surveys. Those that could not be classified into family with confidence were recorded as "unknown coral species".

In addition, a number of benthic characteristics were recorded at each transect. Slope was estimated as Flat (0°-14°), Moderate (15°-74°), Steep (74°-89°), or Vertical (≥90°). The rugosity of the substrate was measured using 5 m weighted rope. The rope was laid along the transect tape following the contours of the reef, and the point along the transect at which the rope ended was recorded. Benthic cover was visually estimated as the proportion of the 5 m x 34 cm transect area taken up by substrate or taxa not suitable for coral settlement – i.e. live hard coral, soft coral, sponge, macroalgae, sand, rubble, etc. (substrate considered suitable for coral settlement included hard bare reefal substrate, rock, crustose coralline algae (CCA) or turf algae).

Statistical Methodology

ANOVA was applied to compare the mean difference in juvenile coral abundance (all juveniles and Acroporidae juveniles) between reefs, years and interaction in reefs and years. A Tukey's 'Honest Significant Difference' (HSD) method was applied if the interaction term was significant.

Variation in spatial and temporal patterns of recruitment were analysed using a repeated measures hierarchical variance partitioning. This is a modified version of GLM (MacNally 2000) with a Poisson fitted function. Hierarchical partitioning calculates goodness of fit measures and, using the partition function, applies the hierarchical partitioning algorithm of Chevan and Sutherland (1991). For the dependent variable (abundance of coral juveniles) the percent contribution of available independent effects (year, reef and site) can be calculated. A permutation test was used to calculate the significance (at a confidence interval of greater than 95%) of each independent effect, in which the significance of z-scores greater than 1.65, equivalent to the 95% confidence interval, are indicated by an asterisk in the tables.

The stock-recruitment relationship, investigating the relationship between percent coral cover to abundance of juveniles, was examined using generalized additive models (GAMs) (Hastie and Tibshirani 1990). These models can accommodate both linear and non-linear relationships. The models were run for all hard coral juveniles and cover, and for the families Acroporidae, Faviidae, Pocilloporidae and Poritidae. All analysis was conducted using the statistical package R (R Development Core Team, 2011).

3.3 Results

3.3.1 Coral Reproduction

Evidence of gametogenic activity was found in an overwhelming majority of corals examined from Ashmore, Cartier and Seringapatam Reefs. The February-March field collections provided 514 coral samples from the predicted autumn spawning period, which were decalcified and examined either by dissection, histology or both. *Porites sp* and Pocilloporids were not dissected due to the smaller polyp sizes, but were processed for histology. Gametes were detected in many species using dissection and stereo microscope (see Figure 3.9-3.11 examples). Of the 374 samples dissected, 307 had visible eggs (82%). Histology was more laboratory intensive, but more sensitive, sometimes enabling the detection of gametes not seen in dissection. A total of 359 samples were processed for histology, of which 333 had gametes (92.7%). Three species, *Fungia sp., Pectinia lactuca and Psammacora sp* had no evidence of gonad. This study demonstrated the importance of combining histology with either *in situ* egg staging or dissections for accurately confirming the presence of gametogenesis. The combined assessment of gamete presence at Ashmore, Cartier and Seringapatam Reefs in all species analysed is shown below in Table 3.1a.

The second coral collection obtained from Ashmore Reef, in September 2011, provided additional evidence of gametogenic activity occurring there, albeit from a limited number of species collected mainly from a single location (S12°13.297, E123°00.760; Figure 3.4)). Divers examined forty of the samples *in situ* and thirty two (80%) contained visible eggs. In subsequent laboratory follow up, ninety one samples from that September 2011 collection were decalcified and examined. Of these seventy one samples (78%) contained eggs in various stages of gametogenesis (Table 3.1b), highly consistent with the field observations. The presence of clearly visible eggs in September points to at least some coral species spawning at Ashmore Reef in the spring. Random coral samples collected from Ashmore Reef on the 12th September 2011 contained visible gametes at various stages of development, but divers recorded sexually mature examples of *Acropora millepora, A. tenuis, A. polystoma, A. gemmifera* and *Goniastrea edwardsii* (Stage 1, see Table 3.1a). The full moon was on the same day, so it seems probable these species spawned in mid-September 2011, 7-10 nights after the full moon.

This would be consistent with bimodal peak spawning seasons observed on both coasts of Australia, with corals in north-west Australia mainly spawning during February-April, but a subset of species spawning in October-November (Rosser & Baird, 2008; Rosser & Gilmour, 2008; Gilmour et al. 2009). The strong inference of a mid-September coral spawning at Ashmore is a novel observation. The current study suggest that for some species the spring may be their major spawning time, while other species appear to be active in both seasons. At Scott Reef, *Goniastrea* species were inferred to spawn only in the autumn (Gilmour et al. 2011), but the Ashmore September samples revealed 100% (n=9) of *Goniastrea edwardsii*, 25% (n=4) *Goniastrea retiformis* and a large proportion of *Acropora millipora* and *A. tenuis* had visible mature eggs present. Similarly this survey confirmed that *A. digitifera* (100%, n=10) and *A. polystoma* (100%, n=8) appear to be able to produce gametes in both seasons.

While the majority of species listed above are known from studies elsewhere to broadcast spawn in a brief seasonal window, often during a multi-species mass spawning event, the analysis of gamete maturity in corals from all three reefs revealed gametes at a variety of developmental stages. There was variation in gamete stage within and between species, as well as within and between reefs, but no clear pattern. Although there were over fifty species of coral sampled, replication of most species was constrained by field conditions and in general was very low. While the spread of gamete stages must be treated with caution, the presence of both very immature and very mature gonad in a species, e.g., *Acropora* digitifera (Table 3.2) is consistent with a bimodal spawn peaks or possibly an even broader timing of seasonal gamete release. There is a suggestion (Table 3.1a) that the

Acroporid species have more variable egg staging than some of the other families, but no consistent trends within or between the three reefs.

Polyp fecundity and egg size variation within and between reefs was investigated using the decalcified, dissected polyp material from a subset of species. There can be some fixation artefacts and distortions associated with preserved material, although all samples were processed in the same manner, so the exact sizes are to some degree relative. Although there were over fifty species of coral sampled, replication of most species was very low. Statistical analyses were carried out for the seventeen species that had replication of at least two samples collected from each of the three reefs; Ashmore, Cartier and Seringapatam. Tests were conducted to compare fecundity and egg size between and within reefs. Polyp fecundity was observed through exact counts for all Acroporid species. It was estimated for all other species by counting the number of eggs per mesentery and multiplying the number of mesenteries per polyp.

The number of eggs per polyp varied within species, but was in the typical range reported elsewhere for these taxa. Within the Acroporiids, polyp fecundity varied from 0 to 19 eggs, while in the massive species fecundity varied from 0 to 480 in a single polyp (Figure 3.12). Egg counts for five of the seven *Acropora* species were significantly different between reefs. In each case, counts were the smallest at Ashmore Reef. All of the other species were significantly different between reefs but there was no clear pattern, with each reef supporting examples of the largest egg numbers for that species. Three species, *Echinopora lamellosa*, *Galaxea fascicularis* and *Goniastrea pectinata* had much higher egg counts on Ashmore Reef than Cartier and Seringapatam. *Goniastrea edwardsii* and *Goniastrea retiformis* had larger egg counts at Seringapatam than the other reefs.

Among the species sampled, there were species which had very similar egg sizes and numbers between Ashmore, Cartier and Seringapatam Reefs, but also species that showed marked differences in these attributes between reefs (Figure 3.13).The mature Acroporiids tended to have the largest eggs, though there was no correlation between egg size and egg count. In other words, the samples with the smallest eggs did not necessarily have the highest number of eggs. Ten out of the 17 species had a significant difference in egg size between reefs, with approximately one third (6/17) found to have larger eggs at Seringapatam than Ashmore and Cartier Reefs (Figure 3.13, Table 3.3). This result may relate mostly to differences in gamete maturity and reflect some level of asynchrony between reefs. For example, *Acropora spicifera* is shown in Figure 3.13 to have much larger eggs in the Seringapatam samples than those from Ashmore, but an analysis of gamete stage (Table 3.2) shows most samples of this species at Seringapatam were at an advanced stage of maturity when collected, while those from Ashmore were quite immature. This may also relate to some degree of reproductive asynchrony between these reefs for some species. Many of the coral species displayed a significant difference within reefs but there was no consistent pattern of gamete stage in relation to reef aspect (Figures 3.14-3.16).

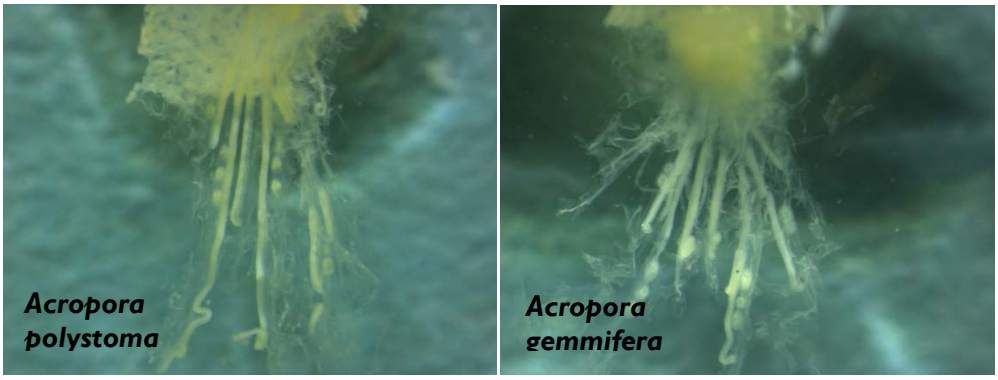


Figure 3.9. Examples of Stage II gametes as seen through the dissection microscope. Stage I eggs are typically too small to be seen using the dissection technique.

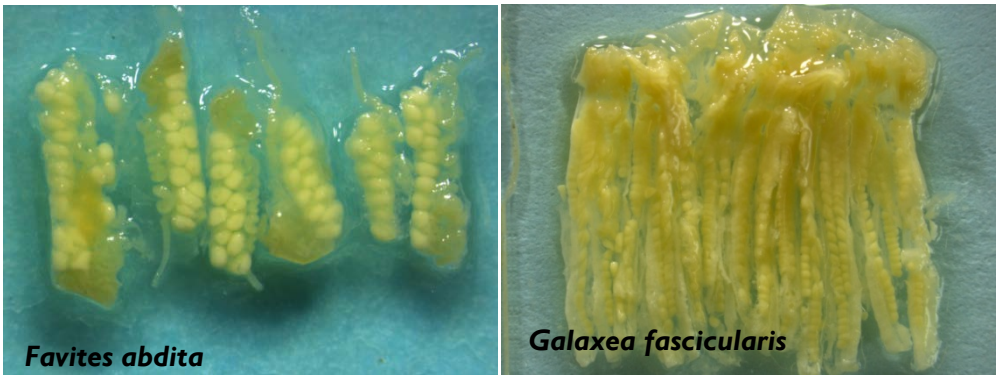


Figure 3.10. Examples of Stage III gametes as seen through the dissection microscope.

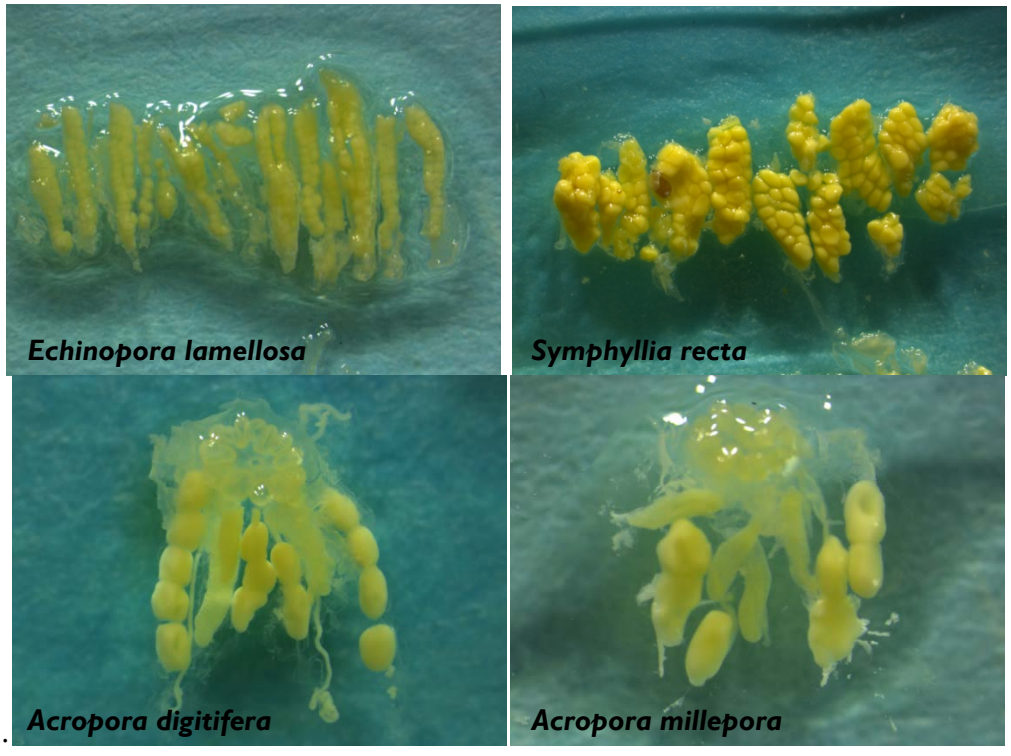


Figure 3.11. Examples of Stage IV gametes as seen through the dissection microscope

Table 3.1a. Number of samples from autumn sampling in Feb/March 2011 exhibiting evidence of gametogenesis. Samples were examined by dissection and histology.

Species	Location	Dissection		Histology	
		N	Evidence of Gametogenesis	N	Evidence of Gametogenesis
Acropora austera	Cartier	1	1	NA	NA
Acropora digitifera	Ashmore	18	13	6	6
	Cartier	7	6	3	3
	Seringapatam	3	2	3	3
Acropora florida	Cartier	1	1	NA	NA
	Seringapatam	1	1	NA	NA
Acropora gemmifera	Ashmore	13	13	8	8
	Cartier	4	4	4	4
	Seringapatam	7	6	7	7
Acropora millepora	Ashmore	5	5	4	4
	Cartier	4	4	4	4
	Seringapatam	4	4	4	4
Acropora palifera	Ashmore	5	5	5	5
	Cartier	4	2	5	5
	Seringapatam	3	3	3	3
Acropora polystoma	Ashmore	6	5	4	4
	Cartier	6	6	4	4
	Seringapatam	4	4	4	4
Acropora robusta	Ashmore	1	0	1	1
	Cartier	6	2	6	6
	Seringapatam	6	5	6	5
Acropora specifera	Ashmore	18	13	11	11
	Cartier	4	4	4	4
	Seringapatam	6	6	6	6
Acropora tenuis	Ashmore	6	5	3	3
	Cartier	4	4	3	3
	Seringapatam	2	2	2	2
Acropora valida	Seringapatam	3	3	NA	NA
Acropora vermiculata	Seringapatam	5	5	NA	NA
Acropora spp.	Ashmore	1	1	NA	NA
Acanthastra echinata	Cartier	3	2	NA	NA
Caulastrea tumida	Ashmore	1	1	NA	NA
Cyphastrea microphthalma	Ashmore	3	2	3	3
	Cartier	3	1	3	2
	Seringapatam	4	4	3	3
Diploastrea heliopora	Ashmore	1	1	1	0
	Cartier	2	0	2	1
	Seringapatam	2	0	2	1

Echinopora lamellosa	Ashmore	3	2	3	3
	Cartier	4	0	4	2
	Seringapatam	6	6	5	5
Favia rotundata	Ashmore	3	1	NA	NA
Favia speciosa	Ashmore	1	1	1	1
	Cartier	1	1	1	1
	Seringapatam	2	1	1	1
Favia spp	Ashmore	3	0	NA	NA
	Cartier	3	2	NA	NA
	Seringapatam	2	2	NA	NA
Favia stelligera	Cartier	3	3	NA	NA
	Seringapatam	4	4	3	3
Favites abdita	Cartier	4	4	3	3
	Seringapatam	3	3	3	3
Favites halicora	Ashmore	1	1	NA	NA
Fungia	Cartier	1	0	NA	NA
	Seringapatam	5	0	NA	NA
Galaxea astreata	Cartier	1	1	1	1
	Seringapatam	5	4	4	3
Galaxea fascicularis	Ashmore	8	8	6	6
	Cartier	4	4	4	2
	Seringapatam	2	2	2	1
Goniastrea edwardsii	Ashmore	6	4	6	5
	Cartier	6	6	6	6
	Seringapatam	9	9	6	6
Goniastrea pectinata	Ashmore	3	3	3	3
	Cartier	3	3	3	3
	Seringapatam	5	5	3	3
Goniastrea retiformis	Ashmore	5	5	4	4
	Cartier	3	3	3	3
	Seringapatam	8	8	5	5
Helipora coerulea	Cartier	2	NA	NA	NA
	Seringapatam	1	NA	NA	NA
Hydnophora rigida	Ashmore	2	2	2	2
	Cartier	5	5	3	3
	Seringapatam	1	1	1	1
Lobophyllia hemprichii	Ashmore	1	1	1	1
	Cartier	1	1	1	0
	Seringapatam	2	1	2	2
Merulina ampliata	Ashmore	2	2	2	2
	Cartier	3	3	3	2
	Seringapatam	3	3	3	3

Montipora (encrusting)	Ashmore	4	4	3	3
	Cartier	4	3	3	3
	Seringapatam	5	5	3	3
Mycedium elephantotus	Ashmore	2	2	NA	NA
Oulophyllia crispa	Cartier	1	1	NA	NA
Pavona varians	Ashmore	1	0	1	1
	Cartier	2	1	2	2
	Seringapatam	4	1	4	4
Pectinia lactuca	Ashmore	1	0	1	0
	Seringapatam	1	0	1	0
Platygyra pini	Ashmore	3	3	3	3
	Cartier	2	1	2	1
Platygyra sinensis	Ashmore	2	1	2	1
	Cartier	2	2	2	2
	Seringapatam	4	4	4	4
Platygyra verweyi	Seringapatam	1	1	NA	NA
Pocillopora damicornis	Ashmore	7	NA	7	7
	Cartier	2	NA	2	2
	Seringapatam	7	NA	7	6
Pocillopora verrucosa	Ashmore	5	NA	5	4
	Cartier	4	NA	3	3
	Seringapatam	7	NA	7	7
Porites (massive)	Ashmore	5	NA	4	4
	Cartier	5	NA	4	4
	Seringapatam	6	NA	4	4
Porites cylindrica	Ashmore	15	NA	13	13
	Cartier	3	NA	3	3
	Seringapatam	4	NA	4	4
Psammocora	Cartier	1	0	NA	NA
Seriatopora aculeata	Cartier	3	NA	NA	NA
Seriatopora hystrix	Ashmore	33	NA	10	10
	Cartier	12	NA	9	9
	Seringapatam	14	NA	9	9
Stylophora pistillata	Cartier	3	NA	2	2
	Seringapatam	2	NA	2	1
Symphyllia radians	Ashmore	2	1	NA	NA
	Cartier	2	2	NA	NA
Symphyllia recta	Ashmore	4	4	4	4
	Cartier	5	5	4	4
	Seringapatam	3	3	3	3
Turbinaria reniformis	Cartier	2	2	NA	NA
	Seringapatam	2	0	NA	NA

Table 3.1b. Number of samples from spring spawning event in Sept. 2011 exhibiting evidence of gametogenesis. Samples were examined by dissection and *in situ* field scoring.

Species	Location	Dissection		In situ Eggs Visible		
		N	Evidence of Gametogenesis	N	No. visible	No. pigmented
Acropora digitifera	Ashmore	10	9	1	0	0/1
Acropora gemmifera	Ashmore	10	10	8	3	2/8
Acropora millepora	Ashmore	10	10	8	8	3/8
Acropora polystoma	Ashmore	8	8	5	5	3/8
Acropora specifera	Ashmore	10	10	NA	NA	-
Acropora tenuis	Ashmore	12	12	9	8	7/9
Acropora spp.	Ashmore	2	2	NA	NA	-
Hydnophora excesa	Ashmore	6	0	NA	NA	-
Galaxea spp. (small)	Ashmore	3	0	1	0	0/1
Galaxea spp. (big)	Ashmore	5	0	NA	NA	-
Goniastrea edwardsii	Ashmore	9	9	8	8	6/8
Goniastrea favulus	Ashmore	2	0	NA	NA	-
Goniastrea retiformis	Ashmore	4	1	NA	NA	-

Table 3.2: Stages of development of eggs and testes derived from histological analysis. ** indicates brooding species with the possibility of containing planulae.

Species	Location	N	Eggs				Testes				Planulae
			I	II	III	IV	I	II	III	IV	
A. digitifera	Ashmore	6	3		2		4		2		
	Cartier	3	1		1	1	1		1	1	
	Seringapatam	3	1			2	1		1	1	
A. gemmifera	Ashmore	8		3	1	1	3	3	1	1	
	Cartier	4		2	1	1		2		2	
	Seringapatam	7	2	4		1	2	4		1	
A. millepora	Ashmore	4		4				4			
	Cartier	4	1			3	1			3	
	Seringapatam	4		2		1		3		1	
A. palifera **	Ashmore	5	3	1	1		3	2			
	Cartier	5	2	1			3	1	1		2
	Seringapatam	3		3				3			
A. polystoma	Ashmore	4	1	3			1	3			
	Cartier	4		4				4			
	Seringapatam	4			2	2			2	2	
A. robusta	Ashmore	1					1				
	Cartier	6	2	1			5	1			
	Seringapatam	6			4	1			4	1	
A. specifera	Ashmore	11	5	6			5	6			
	Cartier	4		2		1	1	2		1	
	Seringapatam	6				6				6	
A. tenuis	Ashmore	3		3				3			
	Cartier	3		2	1			2	1		
	Seringapatam	2			2				2		
Cyphastrea microphthalma	Ashmore	3			3			1	2		
	Cartier	3			1		1		1		
	Seringapatam	3			3				3		
Diploastrea heliopora	Ashmore	1									
	Cartier	2		1				1			
	Seringapatam	2					1				
Echinopora lamellosa	Ashmore	3			2		1		2		
	Cartier	4	1	1			1	1			
	Seringapatam	5	1		3	1	1		3	1	
Favia speciosa	Ashmore	1						1			
	Cartier	1			1				1		
	Seringapatam	1						1			
Favia stelligera	Seringapatam	3			3				3		
Favites abdita	Cartier	3			3				3		
	Seringapatam	3		1	2			1	2		

Galaxea astreata	Cartier	1				1						1			
	Seringapatam	4				3						3			
Galaxea fascicularis	Ashmore	6				5	1					5	1		
	Cartier	4				2						2			
	Seringapatam	2				1						1			
Goniastrea edwardsii	Ashmore	6	1	1	3			1	1	3					
	Cartier	6			6					6					
	Seringapatam	6			6					6					
Goniastrea pectinata	Ashmore	3			2				1	2					
	Cartier	3			3					3					
	Seringapatam	3			3					3					
Goniastrea retiformis	Ashmore	4			4					4					
	Cartier	3		1	2				1	2					
	Seringapatam	5			5					5					
Hydnophora rigida	Ashmore	2			2				1	1					
	Cartier	3		1	2				2	1					
	Seringapatam	1			1					1					
Lobophyllia hemprichii	Ashmore	1			1										
	Cartier	1													
	Seringapatam	2										2			
Merulina ampliata	Ashmore	2			2				1	1					
	Cartier	3			2					2					
	Seringapatam	3			3					3					
Montipora (encrusting)	Ashmore	3	1		2			1		2					
	Cartier	3	1		1	1		1		1	1				
	Seringapatam	3			2	1			1	1	1				
Pavona varians	Ashmore	1							1						
	Cartier	2			1				1						
	Seringapatam	4						1	2		1				
Pectinia lactuca	Ashmore	1													
	Seringapatam	1													
Platygyra pini	Ashmore	3			3					3					
	Cartier	2		1					1						
Platygyra sinensis	Ashmore	2			1					1					
	Cartier	2			2					2					
	Seringapatam	4			4					4					
Pocillopora damicornis **	Ashmore	7			7					7			3		
	Cartier	2	2					2					1		
	Seringapatam	7	3	1		2		3	1		2		1		
Pocillopora verrucosa **	Ashmore	5		2		2			2		2				
	Cartier	3	3					2	1						
	Seringapatam	7	2	3		1		1	5		1				

Porites massive	Ashmore	4			1				3							
	Cartier	4									3	1				
	Seringapatam	4									4					
Porites cylindrica	Ashmore	13			2	1			2		7	1				
	Cartier	3									1	2				
	Seringapatam	4				2						2				
Seriatopora hystrix **	Ashmore	10	2		7	1			2		6	2			6	
	Cartier	9	7		1	1			4		3	2			2	
	Seringapatam	9			2	7						9			4	
Stylophora pistillata **	Cartier	2			2						1	1				
	Seringapatam	2				1		1				1		1		
Symphyllia recta	Ashmore	4				3						4				
	Cartier	4				3		1				3		1		
	Seringapatam	3				2		1				2		1		

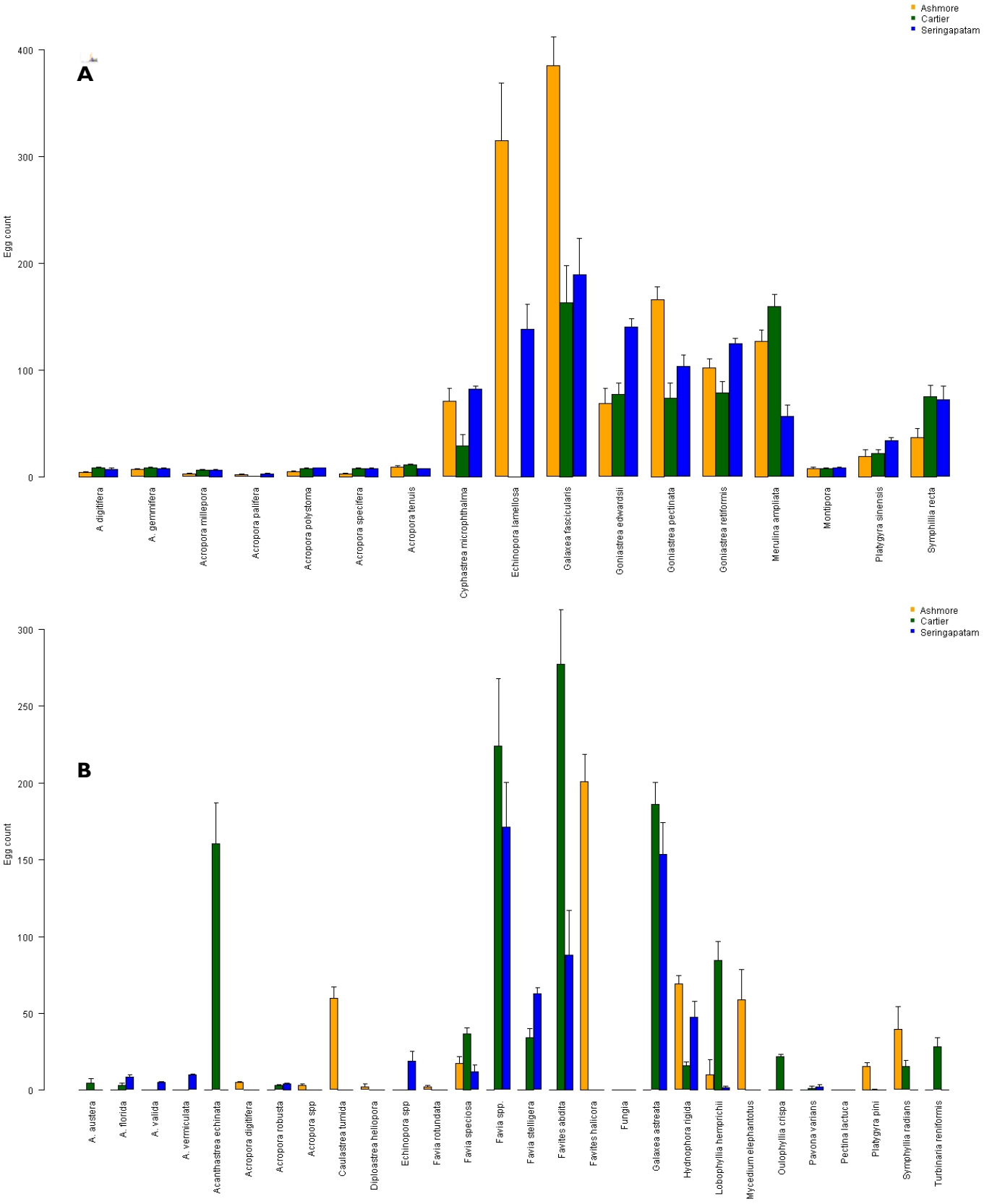


Figure 3.12. Egg counts (+SE) A: Mean polyp fecundity of the 13 coral species with sample replication (at least 2 samples collected from each reef;-Ashmore, Cartier and Seringapatam). For each colony, six polyps were examined. Egg counts are exact for *Acropora spp.* and estimated from the massive forms(number of eggs per mesentery x number of mesenteries per polyp). B: Mean polyp fecundity of all other species.

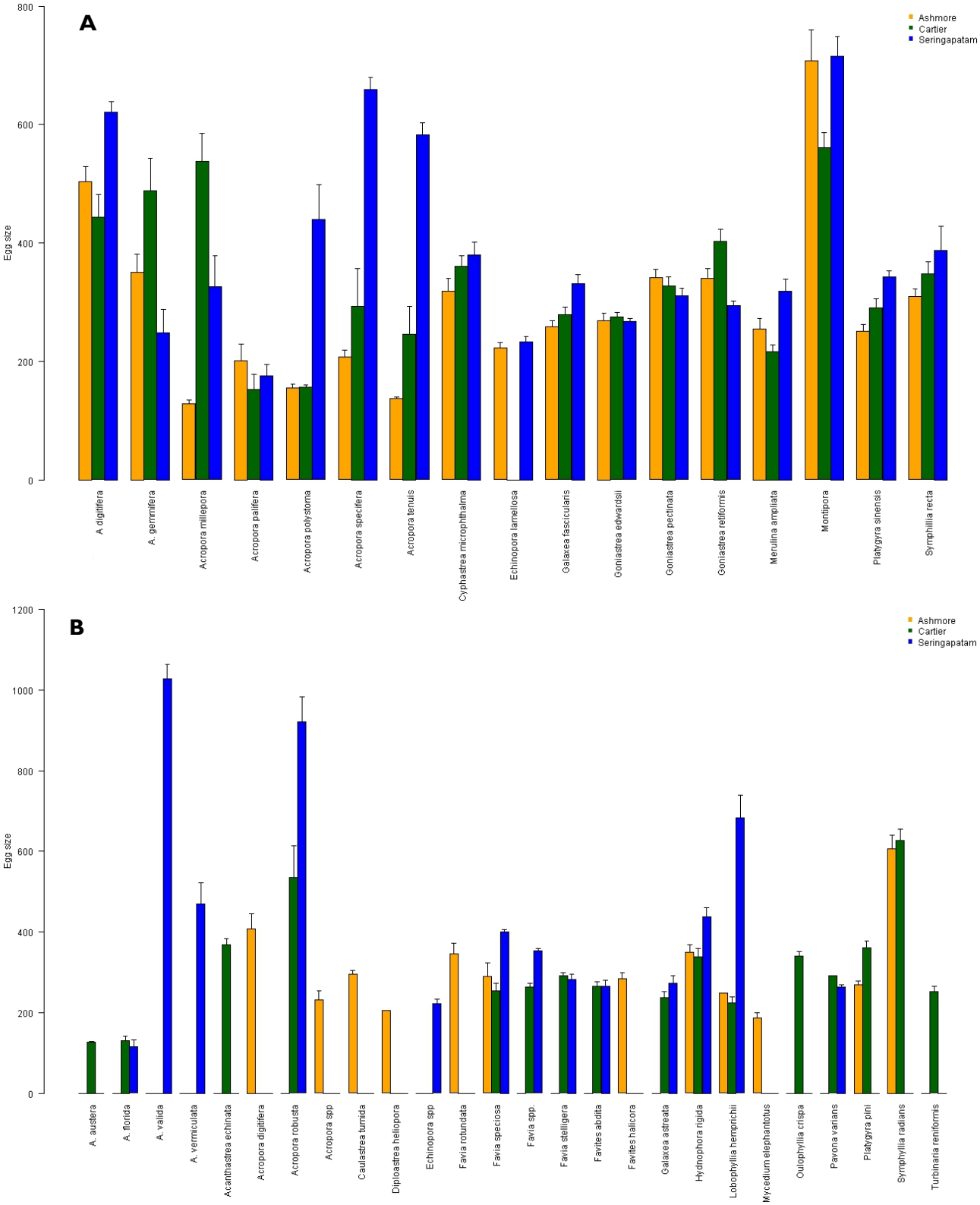


Figure 3.13. Egg Size (+SE). A: Mean egg size of the 13 coral species with sample replication (at least 2 samples collected from each reef;-Ashmore, Cartier and Seringapatam). Six polyps were examined per colony sample. All eggs were measured for *Acropora spp.* and a sample of 10 eggs was measured for massive forms. B: Mean egg size for all other species.

Table 3.3. Summary of results of ANOVA T test for egg count and egg size of species with at least two samples from each location (Ashmore, Cartier and Seringapatam Reefs), between reefs and within each reef.

	Between Locations		**Ashmore**		**Cartier**		**Seringapatam**	
	Egg count	**Egg size**	**Egg count**	**Egg size**	**Egg count**	**Egg size**	**Egg count**	**Egg size**
Acropora digitifera	**<0.0001**	0.021	**<0.0001**	**<0.0001**	**0.033**	**<0.0001**	**<0.0001**	NA
Acropora gemmifera	0.216	0.002	**0.001**	**<0.0001**	0.13	**0.036**	**<0.0001**	**<0.0001**
Acropora millepora	**<0.0001**	**<0.0001**	0.323	**<0.0001**	**0.02**	0.163	**0.007**	**<0.0001**
Acropora palifera	**0.003**	**<0.0001**	**0.001**	0.078	0.126	NA	0.719	0.154
Acropora polystoma	**0.0002**	**<0.0001**	**0.0003**	0.099	0.687	**0.034**	**0.015**	**0.021**
Acropora specifera	**<0.0001**	**<0.0001**	**0.007**	**<0.0001**	0.211	**<0.0001**	**0.02**	0.176
Acropora tenuis	0.158	**<0.0001**	**0.0002**	**0.028**	0.29	**<0.0001**	0.108	0.671
Montipora	0.833	**0.02**	**0.001**	**0.016**	**0.009**	**0.0001**	**0.017**	0.121
Cyphastrea microphthalma	**0.0001**	0.178	**0.039**	0.195	**<0.0001**	NA	0.338	**0.007**
Echinopora lamellosa	**<0.0001**	0.454	**0.037**	**0.0003**	NA	NA	0.082	**0.015**
Goniastrea edwardsii	**<0.0001**	0.705	**0.0003**	0.739	**<0.0001**	**0.02**	**<0.0001**	**0.0005**
Goniastrea pectinata	**<0.0001**	0.281	NA	NA	**0.0003**	0.691	**<0.0001**	0.088
Goniastrea retiformis	**0.0002**	**<0.0001**	**<0.0001**	0.564	**0.05**	**0.026**	**<0.0001**	0.108
Symphyllia recta	**0.022**	0.108	0.471	0.529	**<0.0001**	**<0.0001**	0.264	**<0.0001**
Merulina ampliata	**<0.0001**	**0.0001**	NA	NA	**0.001**	0.32	**0.002**	**0.021**
Platygyra sinensis	**0.018**	**0.0002**	**<0.0001**	NA	NA	NA	0.14	0.263
Galaxea fascicularis	**<0.0001**	**0.004**	0.147	**<0.0001**	**0.001**	0.485	0.177	0.309

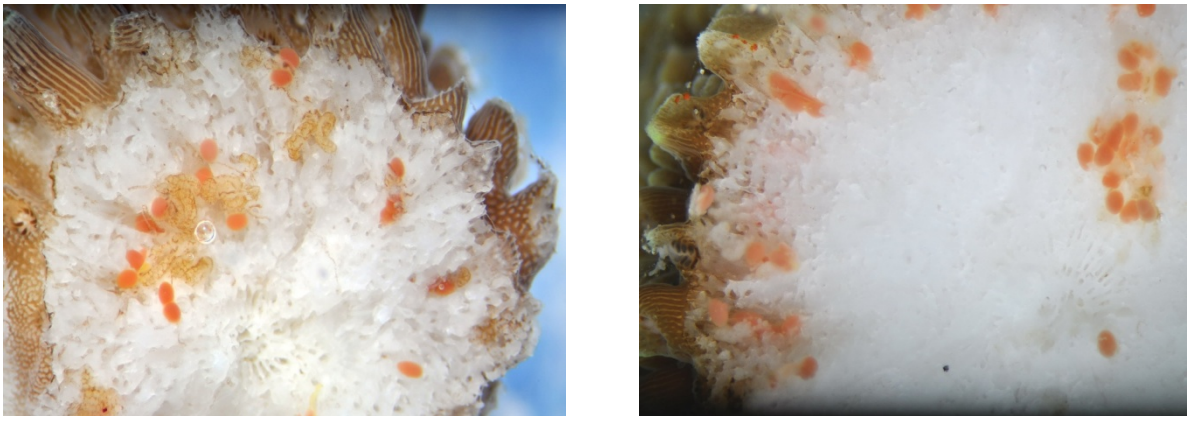


Figure 3.14. Regional reproductive synchrony: *Acropora robusta* branch cross sections from Cartier Islet (left image) collected on 14th February 2011 and Scott Reef (right image) collected on 17th February 2011 demonstrate mature gonads at the same stage of development (Score 1). The strongly pigmented oocytes and well developed testes in this species suggest it would most likely spawn at both reefs in February following the full moon on the 18th.

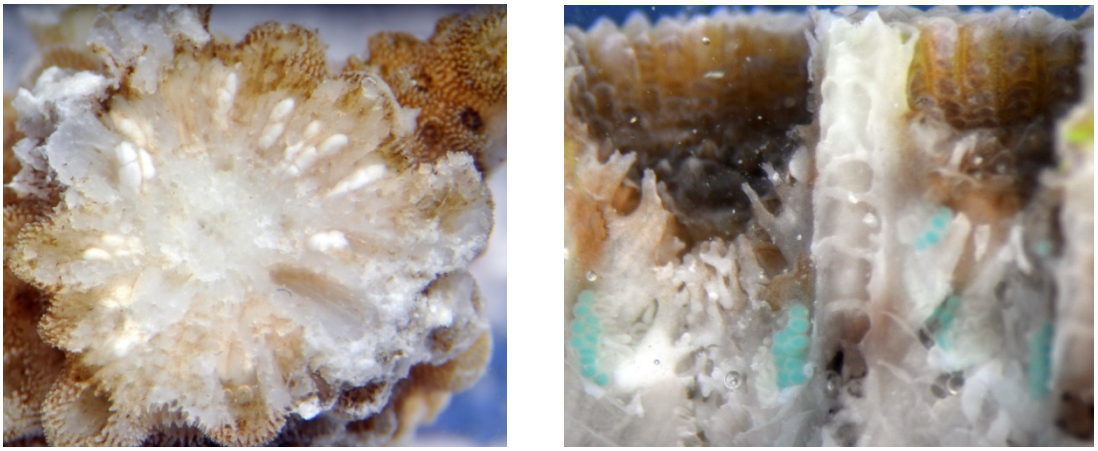


Figure 3.15. Developing gonads: fresh polyp cross sections in *Acropora verweyi* (left image) and *Favia speciosa* reveal visible oocytes which were not yet fully mature when collected in mid-February, indicating a likely spawning period in late March 2011. Most species with visible gonad were at this stage of development during the field survey in mid-February, with white or lightly pigmented oocytes and small, simple testes.

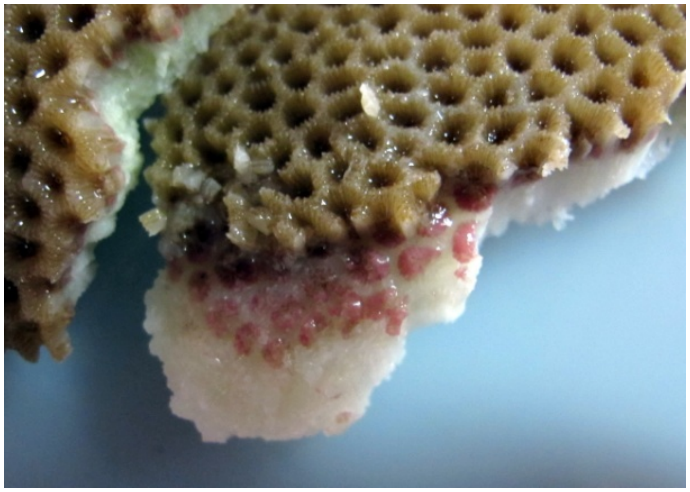


Figure 3.16. *Goniastrea edwardsii:-* Ashmore Reef, 12th September 2011. The pink eggs in this species indicate it is mature and would likely have spawned around the 20th September.

Coral recruitment results

Results for the mean number of coral recruits per tile are detailed for all recruits and each taxonomic group in Table 3.4. Mean coral recruits per tile (all families combined) at Ashmore (4.01 ± 0.3 SE) and Cartier (8.41 ± SE 1.3) were not significantly different to the main control reef Seringapatam (6.25 ± 0.7 SE). Mean recruits per tile were significantly higher at the second control reef Scott Reef (53.49 ± 6.6 SE) compared with the other three reefs (Figure 3.17, Tables 3.5). The high recruitment rate at Scott Reef was due to a very high number of Acroporidae recruits per tile (46.6 ± 6.0 SE) compared with the other studied reefs, Seringapatam (1.8 ± 0.4 SE) Ashmore (0.63 ± 0.09 SE) and Cartier (0.21 ± 0.05 SE) as well as a higher number of recruits classed as Others (Figures 3.17, 3.18, Tables 3.4, 3.5). T-tests found recruits from the family Acroporidae to be significantly different at all reefs (Tables 3.5, 3.6).

Poritidae recruits were significantly higher at Cartier (6.2 ± 1.18 SE) than at the other three reefs, and lowest at Scott Reef (0.29 ± 0.07 SE). Pocilloporidae recruit numbers were relatively low at all reefs (between 1.46 and 1.99 mean recruits per tile) and no significant difference in Pocilloporidae recruitment was seen between any of the reefs. Recruits classed within the group Others were significantly higher at Scott Reef (4.98 ± 0.68 SE) than at the other three reefs.

Dominant families

Acroporidae was the coral family with the highest overall numbers on the recruitment tiles, and was the dominant recruit family at Scott Reef. However Acroporidae was not the dominant recruit group at all the studied reefs. At Ashmore, Pocilloporidae dominated by a small margin. Poritidae recruits dominated at Cartier, particularly at the south-west location C2, and the north-west location C3. At Seringapatam, Acroporidae, Pocilloporidae and Poritidae were approximately equal in abundance across recruitment tiles but variable between locations, with Acroporidae high on the easterly locations SR3 and SR4, and Poritidae dominating at the south-west location SR6 (Figure 3.18).

Variance partitioning analysis

Recruitment of corals and other marine organisms with planktonic larvae is characteristically variable at all spatial scales. In this study, most of the spatial variation in recruitment occurred at the location scale, referring to the 6-8 sites around the three main reefs (see Figure 3.19), which accounts for approximately 75% of the variation in the data (Figure 3.15, Table 3.7). About 25% of the variation in recruitment occured between the four study reefs, and is significantly different. The variation amongst tiles and sites was not significant.

Stock Recruitment relationship

Mean coral recruitment for most of the taxonomic groups was not strongly dependent on the adult coral cover at the location scale, the exception being the brooding corals of the family Pocilloporidae. A slightly positive relationship (R^2=0.132p=0.045) was seen between total hard coral cover and recruitment (all families) at the location level (Figure 3.20, Table 3.8). The strongest stock-recruitment relationship was seen for Pocilloporidae corals (R^2= 0.363p=0.001). No relationship between recruitment and adult cover was seen for the other family groups.

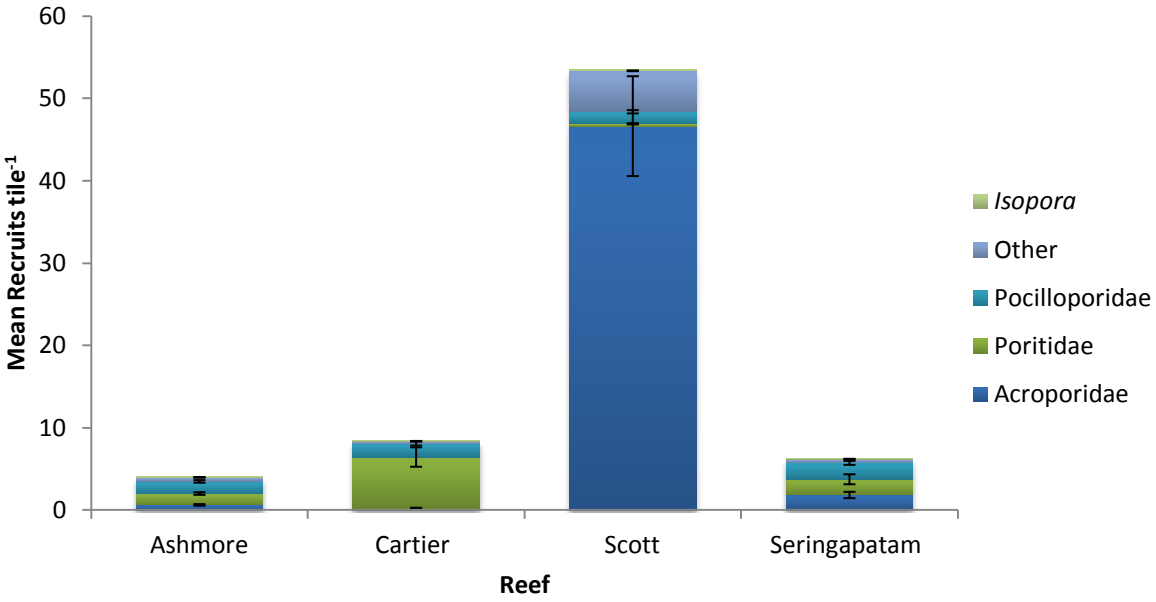


Figure 3.17. Mean number of recruits per tile (±SE) separated into the taxonomic groups Acroporidae, Poritidae, Pocilloporidae, *Isopora* and Others at each of the studied reefs. A regional map of the reefs can be seen in Figure 1.1.

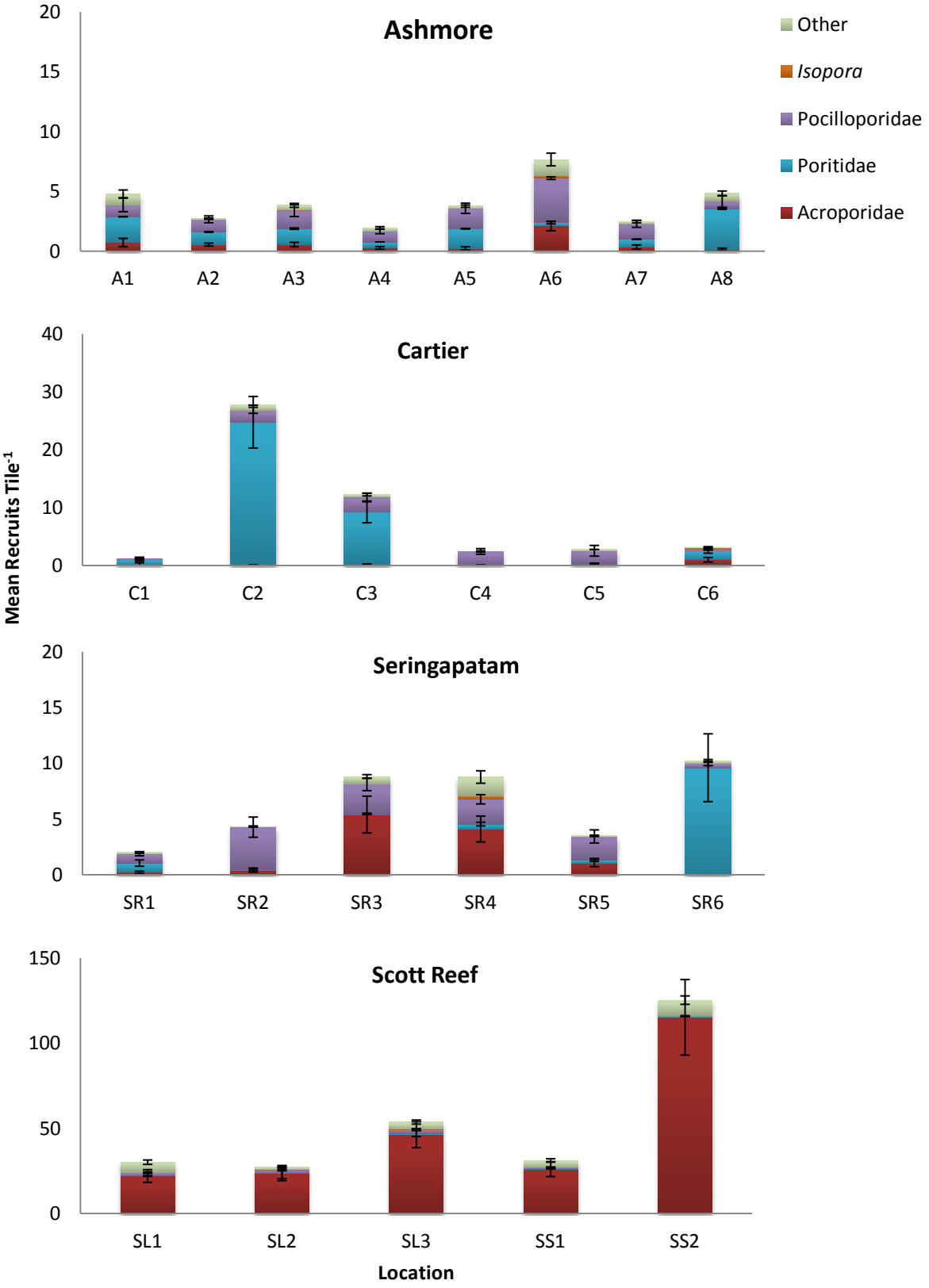


Figure 3.18. Mean number of recruits per tile ± SE at each location for Ashmore, Cartier, Seringapatam and Scott Reefs, separated into the taxonomic groups; Acroporidae, Poritidae, Pocilloporidae, *Isopora* and Others. Note different axis scales.

Table 3.4. Descriptive statistics for mean number of coral recruits per tile for All Recruits and for each of the taxonomic groups: Acroporidae, *Isopora,* Pocilloporidae and Poritidae. At Ashmore and Cartier Reefs, and the control Reefs, Seringapatam and Scott.

Family	Reef	Mean	N	Std. Error of Mean	Minimum	Maximum
Total	Ashmore	4.01	142	0.321	0	21
	Cartier	8.41	107	1.313	0	88
	Seringapatam	6.25	107	0.799	0	52
	Scott Reef	53.48	90	6.633	5	337
	Total	15.58	446	1.655	0	337
Acroporidae	Ashmore	0.63	142	.092	0	6
	Cartier	0.21	107	.059	0	3
	Seringapatam	1.83	107	.383	0	24
	Scott Reef	46.62	90	6.064	3	300
	Total	10.10	446	1.501	0	300
Isopora	Ashmore	0.04	142	.017	0	1
	Cartier	0.05	107	.031	0	3
	Seringapatam	0.07	107	.040	0	4
	Scott Reef	0.14	90	.046	0	2
	Total	0.07	446	.016	0	4
Other	Ashmore	0.49	142	.094	0	8
	Cartier	0.28	107	.056	0	3
	Scott Reef	4.98	90	.683	0	34
	Seringapatam	0.46	107	.114	0	9
	Total	1.34	446	.168	0	34
Pocilloporidae	Ashmore	1.47	142	.155	0	10
	Cartier	1.64	107	.247	0	16
	Scott Reef	1.46	90	.200	0	7
	Seringapatam	1.99	107	.240	0	13
	Total	1.63	446	.105	0	16
Poritidae	Ashmore	1.38	142	.158	0	9
	Cartier	6.22	107	1.181	0	81
	Seringapatam	1.91	107	.606	0	51
	Scott Reef	0.29	90	.076	0	4
	Total	2.45	446	.338	0	81

Table 3.5. Results of ANOVA comparing the number of coral recruits per tile between the studied reefs. For All Recruits, and then for each taxonomic group: Acroporidae, Pocilloporidae, Poritidae, and Others.

		Df	Sum Sq	Mean Sq	F value	P value
All Recruits	Reef	2	3.83	1.915	2.115	0.1222
	Residuals	353	319.65	0.906		
Acroporidae	Reef	2	12.014	6.007	18.556	**<0.0001**
	Residuals	353	114.269	0.324		
Pocilloporidae	Reef	2	1.579	0.789	1.568	0.209
	Residuals	353	177.754	0.504		
Poritidae	Reef	2	23.614	11.807	13.93	**<0.0001**
	Residuals	353	299.210	0.848		
Other	Reef	2	0.449	0.225	1.236	0.292
	Residuals	353	64.131	0.182		

Table 3.6. Results of t-test comparing mean number of recruits between each of the studied reefs, for All Recruits, then for each taxonomic group: Acroporidae, Poritidae and Others. Significant values in bold. Note ANOVA showed no significant effect of reef for the family Pocilloporidae, so no t-tests were performed.

Family		t	df	p-value
All Recruits	Ashmore vs Cartier	-1.823	176.658	0.070
	Ashmore vs Seringapatam	-1.625	197.781	0.106
	Cartier vs Seringapatam	0.328	206.860	0.743
Acroporidae	Ashmore vs Cartier	4.236	243.831	**<0.0001**
	Ashmore vs Seringapatam	-2.879	163.120	**0.005**
	Cartier vs Seringapatam	-5.615	139.785	**<0.0001**
Poritidae	Ashmore vs Cartier	-3.634	153.353	**<0.0001**
	Ashmore vs Seringapatam	1.530	200.750	0.128
	Cartier vs Seringapatam	4.384	185.486	**<0.0001**

NOTE: No Faviidae in the Recruitment data.

Table 3.7. Permutation test for hierarchical partitioning of variation in number of recruits (all families) contributed by the spatial scales studied; Tile, Site, Location and Reef.

	Obs	Z score	Significant (95%CI)
Tile	0.00	-0.40	
Site	0.00	0.29	
Location	0.40	24.25	*
Reef	0.15	29.77	*

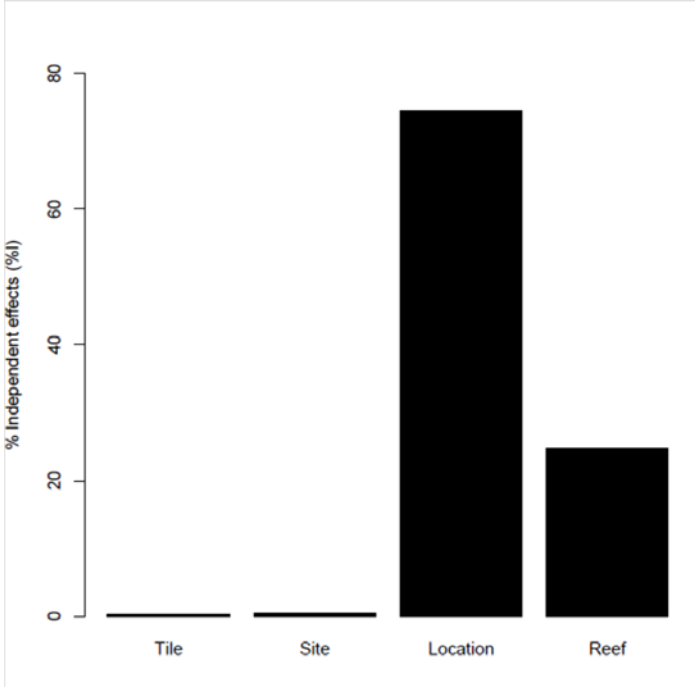


Figure 3.19. Graph of variation partitioning analysis showing the amount of variation in recruitment accounted for by each of the four spatial scales studied: Tile, Site, Location and Reef.

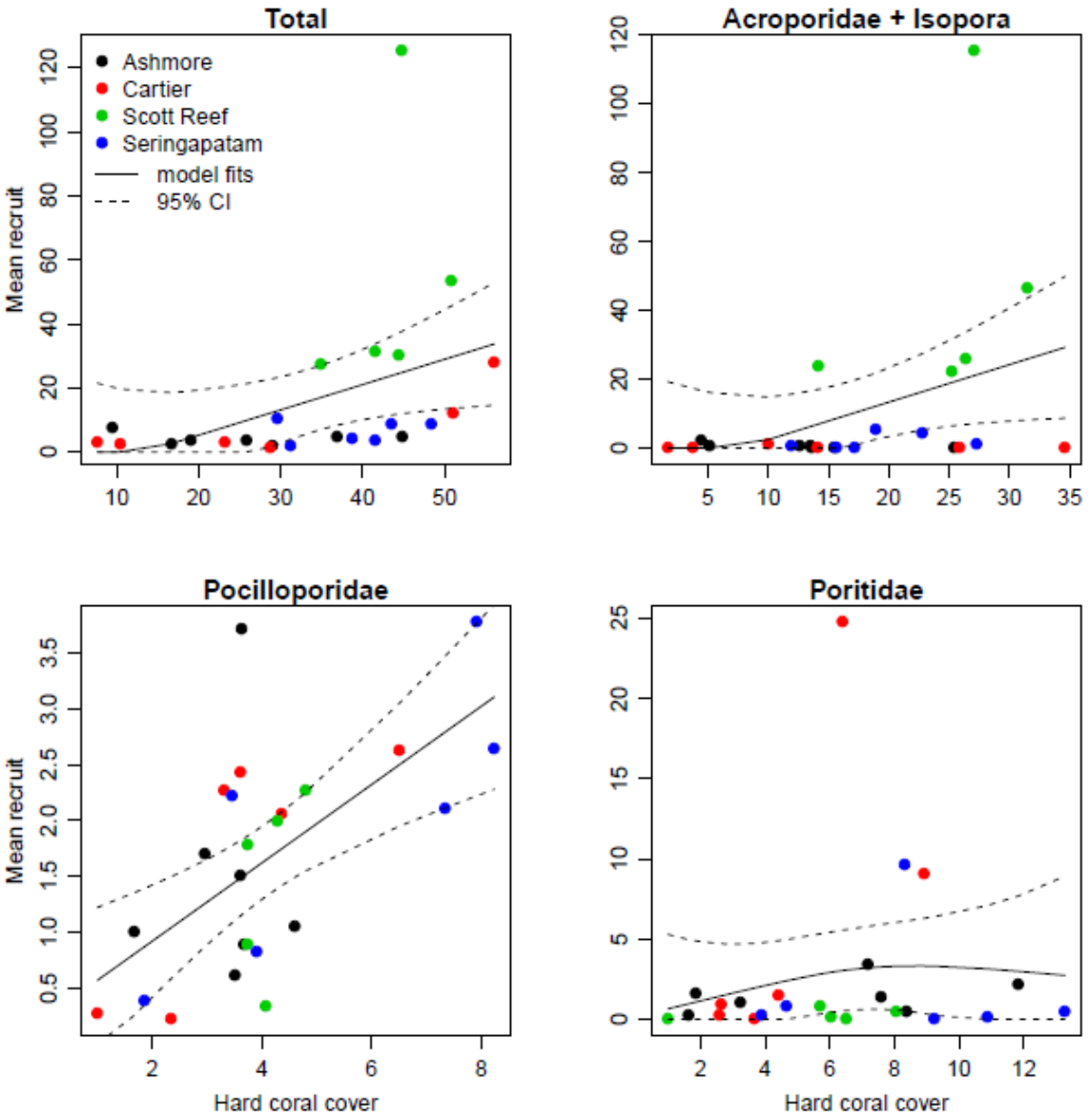


Figure 3.20. Stock recruitment relationship – comparing % coral cover to mean recruits per tile at each location. Points are observed values, solid line is the mean predicted fit from GAM and dash lines are 95% confidence intervals. Colours indicate the four study reefs. a) Total hard coral cover (%) and total recruitment (mean recruits per tile), b) Acroporidae cover and recruitment, c) Pocilloporidae cover and recruitment, d) Poritidae cover and recruitment.

The overall trend is a weak positive correlation between total number of recruits and coral cover, but this is principally being driven by strong stock recruitment relationship in the Pocilloporidae family.

Table 3.8. Summary of GAM examining the relationship between numbers of recruits versus local adult hard coral cover.

	edf	Ref.df	F	P	R^2
Total	1.000	1.000	4.507	**0.045**	0.132
Acroporidae	1.000	1.000	4.041	0.057	0.117
Pocilloporidae	1.000	1.000	14.090	**0.001**	0.363
Poritidae	1.403	1.701	0.298	0.710	0.002

Juvenile Counts Results

Mean abundance of juvenile corals (<5 cm colonies, all families grouped together) at Ashmore (12.1 ± 0.8 SE) and Cartier (10.8 ± 1.5 SE) was not significantly different to that at the main control reef Seringapatam (13.0 ± 0.9 SE) in 2010. However, juvenile coral abundance at the two locations surveyed at Scott Reef in 2010 (25.8 ± 5.5 SE) was significantly higher than all other studied reefs (Figure 3.21, Tables 3.9, 3.12). In 2011, mean juvenile abundance increased at Ashmore (13.7 ± 0.5 SE), Cartier (13.4 ± 1.2 SE) and Seringapatam (14.2 ± 0.7 SE) compared to 2010. However, this increase was only significant at Ashmore (Table 3.13). In 2011 there was no significant difference in mean juvenile coral abundance between the three studied reefs (Tables 3.10, 3.11, 3.13). Juvenile coral abundance was not studied at Scott Reef in 2011.

Dominant Families

Acroporidae was the most abundant family of juvenile corals at all studied reefs (Figure 3.22, 3.23). At Ashmore, Cartier and Seringapatam, Acroporidae juveniles were at relatively similar mean abundances per transect (between 4-7) in 2010 and 2011. In the survey of two locations (SL1 and SL2) at Scott Reef in 2010. However, abundances of Acroporidae juveniles were significantly higher than at the other studied reefs. Pocilloporidae, Poritidae and Faviidae were the other dominant families.

Stock Recruitment relationship

Juveniles vs Coral cover: A significant positive relationship was seen between coral cover and mean juvenile abundance per location at the surveyed reefs (2010 and 2011 data combined), driven by Acroporidae and Pocilloporidae. However, a significant positive relationship was not found for the other major coral family groups (Figure 3.24; Table 3.14)

Juveniles vs Recruits: A General Additive Model found a slightly positive relationship between juvenile abundance and mean number of recruits per survey tile (all families combined) at each location surveyed in 2011. However, no significant relationship was found when each of the major coral families were treated separately (Figure 3.25, Table 3.15).

Size classes

Juvenile coral colonies were measured to the nearest centimetre in 2011, in order to determine whether certain cohorts of juvenile corals were missing, or noticeably different, between the study reefs. The size class distribution of juvenile corals in 2011 was relatively similar between both experimental reefs, Ashmore and Cartier and the main control reef, Seringapatam, and there is no outstanding lack of cohorts at any reef (Figure 3.26).

Spatial variation in juvenile recruitment

Coral recruitment and post settlement mortality is highly spatially variable at all scales. A partitioning of variance analysis showed that far more variation in juvenile coral abundance occurred within a location than between the experimental reefs (Figure 3.27, Table 3.16).

Comparison with Great Barrier Reef (GBR) data

Due to the lack of Juvenile coral survey data at these reefs prior to the possible disturbance, a comparison was made to outer GBR reefs surveyed within the AIMS Long-Term Monitoring Program with similar live hard coral cover to the reefs studied in this survey. Live hard coral cover at Ashmore and Cartier in 2010 was approximately 20-26% on the shallow and deep slope sites in 2010. Seringapatam had approximately 20% hard coral cover in the shallow and 36% at the deep slope. In 2011, mean hard coral cover increased by approximately 2-4% at all reefs. The outer GBR reefs with 21-25% coral cover were found to have a mean juvenile density of 13.5 per m^2 (± 5 SE), reefs with 26-30% coral cover had a mean juvenile coral density of 14 per m^2 (± 6 SE). Juvenile coral density per m^2 at Ashmore (10.2 ± 1.05 SE) was slightly lower than this average in 2010, Seringapatam (12.9 ±1.3 SE) in 2010 was within the lower range (Figure 3.28; Table 3.9). All three reefs were within or above the GBR average in 2011.

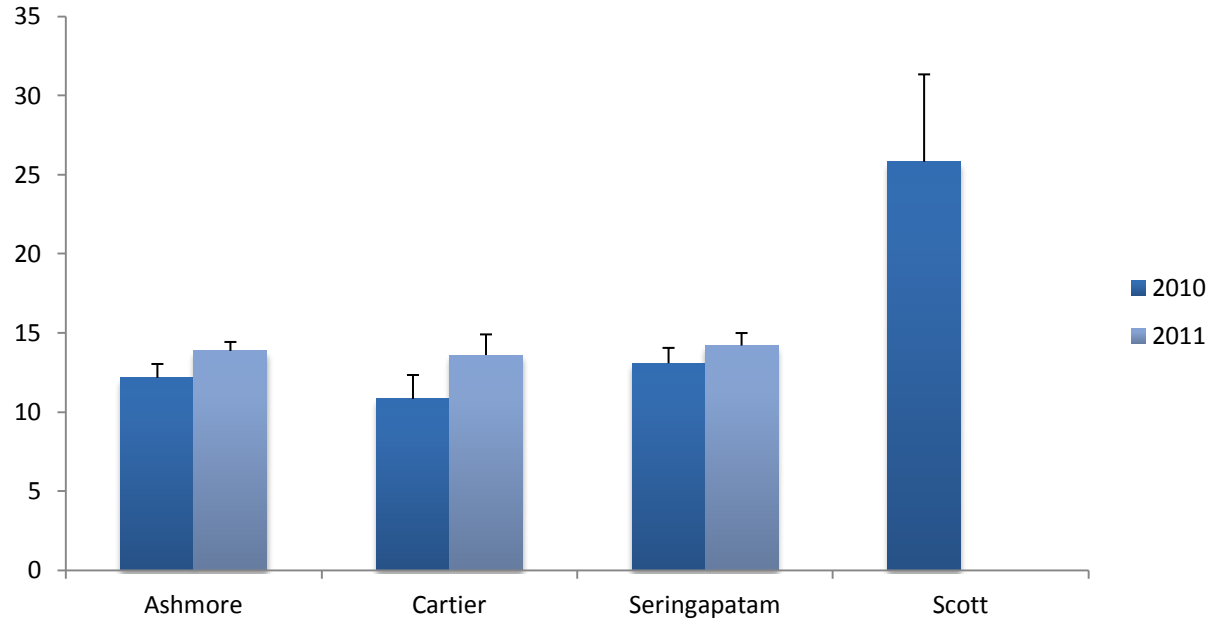


Figure 3.21. Mean abundance(+SE) per transect for juvenile coral**s (≤5cm) at** each of the main studied reefs: Ashmore, Cartier and Seringapatam, and the secondary control reef Scott Reef. Juvenile corals were not surveyed at Scott Reef in 2011.

Table 3.9. Mean abundance and mean density per transect for juvenile corals at each of the studied reefs in 2010 and 2011.

Year	Reef	n	Mean Abundance	S.E. of Abundance	Mean Density m^{-2}	S.E. of Density
2010	Ashmore	54	12.16666667	0.875056153	10.21525034	1.053042537
	Cartier	36	10.83333333	1.512645113	17.32049875	2.464572812
	Seringapatam	66	13.09090909	0.967954437	12.9619244	1.370621726
	Scott	11	25.81818182	5.526495161	24.1426749	8.146679702
2011	Ashmore	96	13.86458333	0.569051957	21.13375145	1.716539524
	Cartier	71	13.6056338	1.304762808	18.4751198	1.795961821
	Seringapatam	72	14.20833333	0.789191832	17.164108	1.52043956

Table 3.10. Results of ANOVA comparing the abundance of juvenile corals between reefs and years.

	Df	Sum Sq	Mean Sq	F value	P value
Reef	3	12.021	4.0069	9.878	**<0.0001**
Year	1	2.471	2.471	6.092	**0.014**
Reef*Year	2	0.302	0.151	0.372	0.689
Residuals	316	128.182	0.406		

Table 3.11 Results of ANOVA comparing the abundance of juvenile corals between reefs for 2010 and 2011.

Year		Df	Sum Sq	Mean Sq	F value	P value
2010	Reef	3	2011	670.32	8.773	**<0.0001**
	Residuals	163	12454	76.40		
2011	Reef	2	0.9	0.440	0.006	0.994
	Residuals	153	11274.0	73.686		

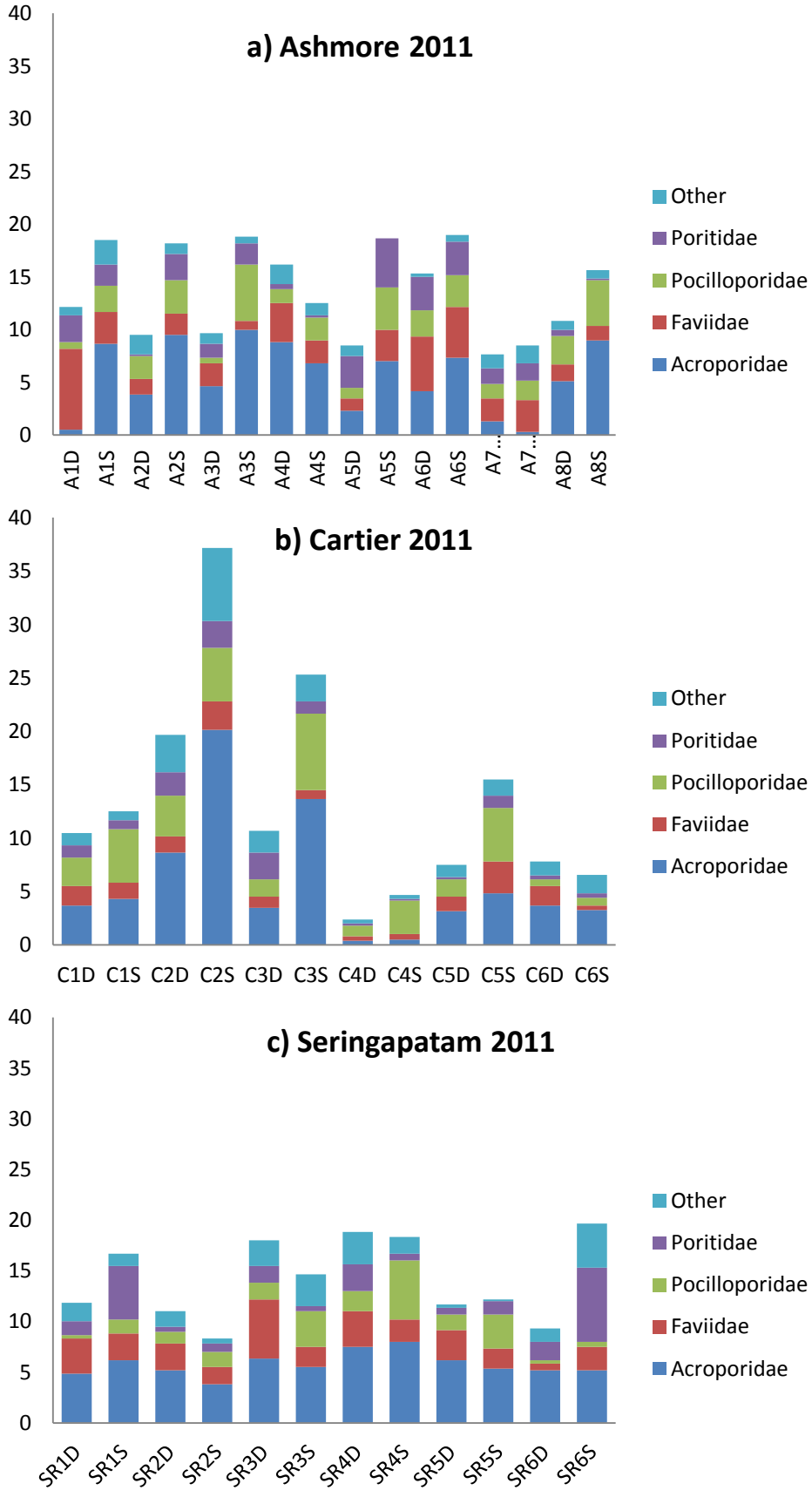


Figure 3.22. Mean abundance of juvenile corals (<5 cm) at each location for a) Ashmore, b) Cartier and c) Seringapatam. Separated into the major families; Acroporidae, Faviidae, Pocilloporidae, Poritidae and Others.

Table 3.12. Tukey HSD comparing the abundance of juvenile corals between reefs for 2010. Note that Tukey HSD was not performed for 2011 data as there was no significant effect between reefs.

	diff	lower	Upper	P value (adj)
Cartier-Ashmore	-1.333	-6.215	3.549	0.893
Scott-Ashmore	13.652	6.146	21.157	**<0.0001**
Seringapatam-Ashmore	0.924	-3.239	5.088	0.939
Scott-Cartier	14.985	7.168	22.801	**<0.0001**
Seringapatam-Cartier	2.258	-2.443	6.959	0.598
Seringapatam-Scott	-12.727	-20.116	-5.338	**<0.0001**

Table 3.13. Results of ANOVA comparing the abundance of juvenile corals between 2010 and 2011 for each of the studied reefs.

		Df	Sum Sq	Mean Sq	F value	P value
Ashmore 2010-2011	Year	1	156.5	156.481	4.175	**0.044**
	Residuals	106	3972.7	37.478		
Cartier 2010-2011	Year	1	256.9	256.89	1.855	0.178
	Residuals	70	9693.6	138.48		
Seringapatam 2010-2011	Year	1	60.0	60.008	1.164	0.283
	Residuals	130	6701.7	51.552		

Table 3.14. Generalized additive model (GAM) results investigating the stock-recruitment relationship between percent coral cover and juvenile abundance (all locations) for each of the major taxonomic groups.

	edf	Ref.df	F	P
Total	1.535	1.784	6.328	**0.003**
Acroporidae	1.000	1.000	37.070	**<0.0001**
Faviidae	1.499	1.749	1.242	0.287
Pocilloporidae	1.924	1.994	9.714	**<0.0001**
Poritidae	1.721	1.922	1.982	0.141

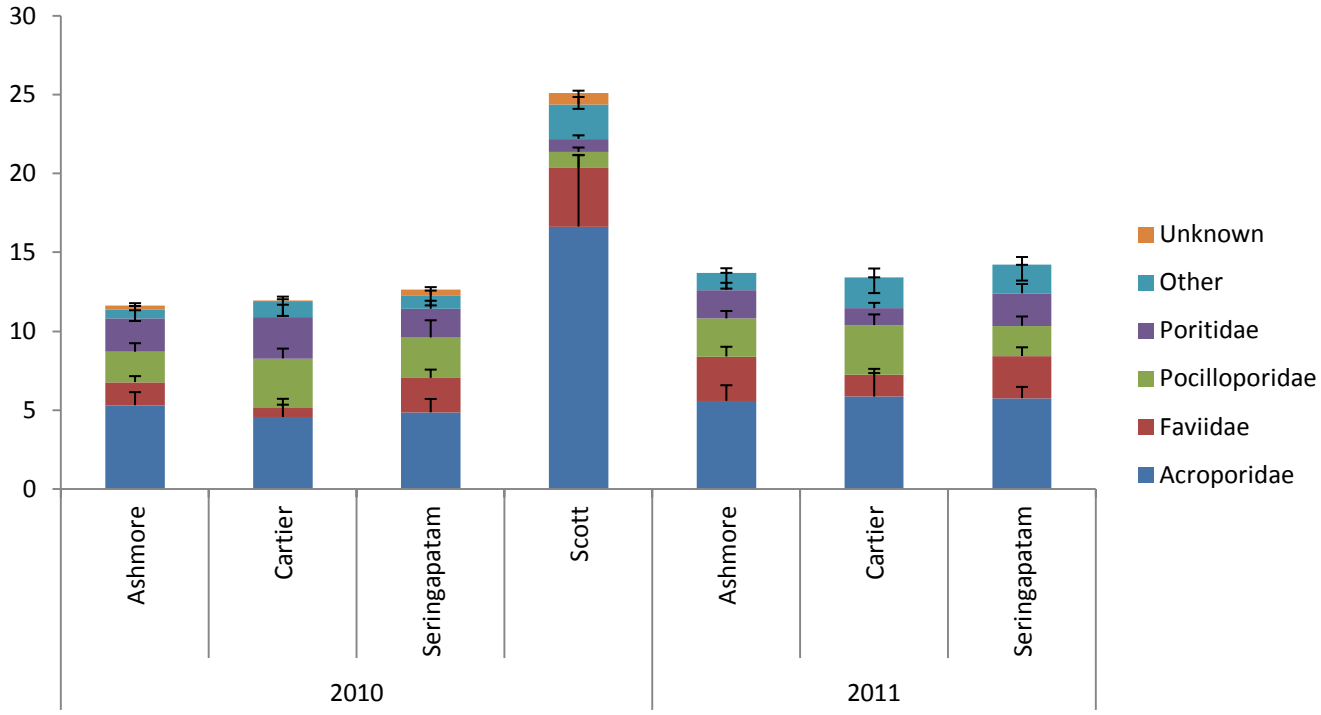


Figure 3.23. Mean abundance (+SE) **per transect for juvenile corals (≤** 5cm) at each of the main studied reefs: Ashmore, Cartier and Seringapatam, and the secondary control reef Scott Reef, separated into the four most abundant coral families Acroporidae, Faviidae, Pocilloporidae and Poritidae, and Other. Juvenile corals were not surveyed at Scott Reef in 2011.

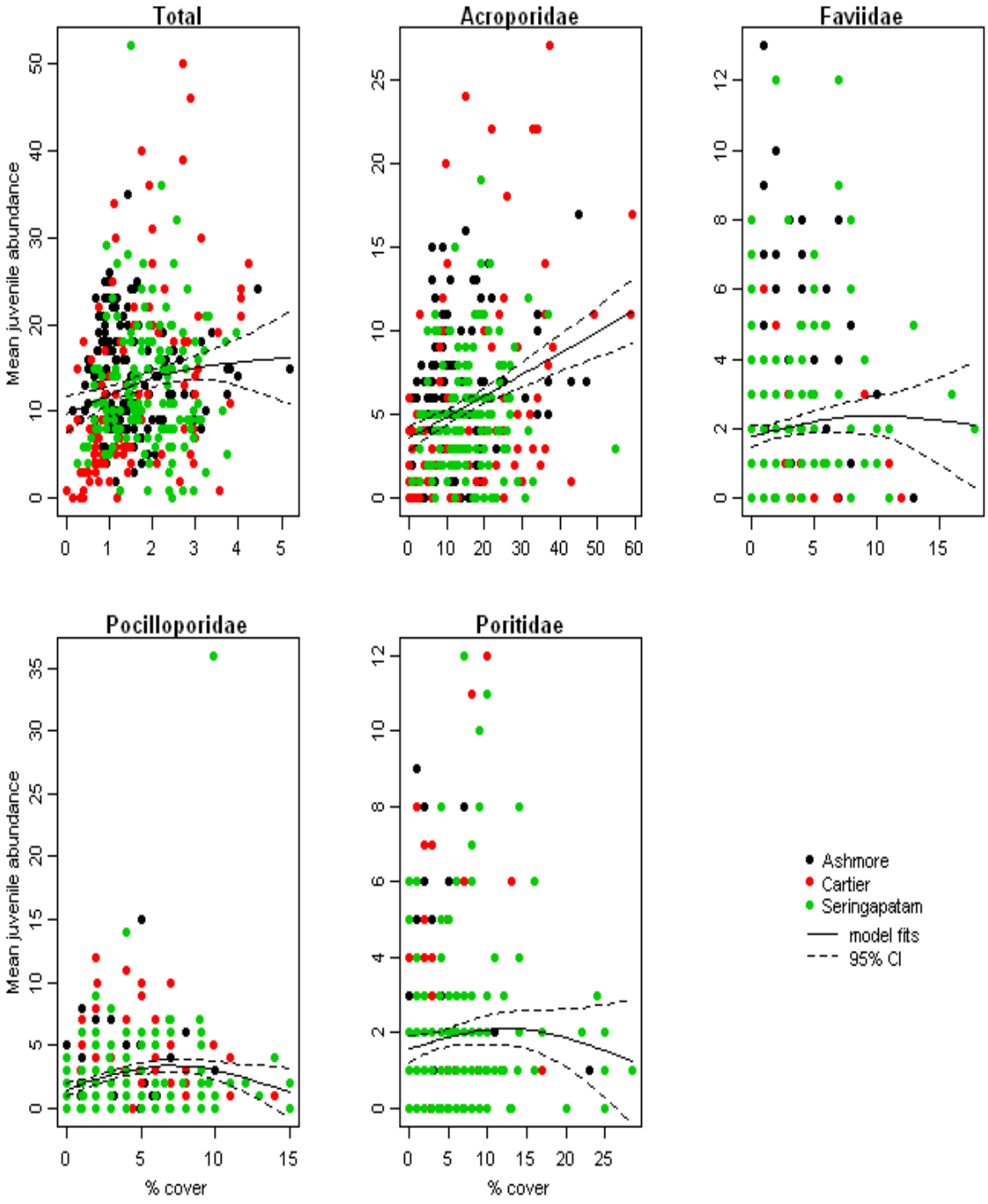


Figure 3.24. Stock recruitment relationship – comparing % coral cover to mean abundance of juvenile corals per transect at each location. Points are observed values, solid line is the mean predicted fit from GAM and dash lines are 95% confidence intervals. Colours indicate the four study reefs. a) Total hard coral cover (%) and total juvenile abundance (mean juvenile corals per transect), b) Acroporidae cover and juveniles, c) Faviidae cover and juveniles, d) Pocilloporidae cover and juveniles, e) Poritidae cover and juveniles.

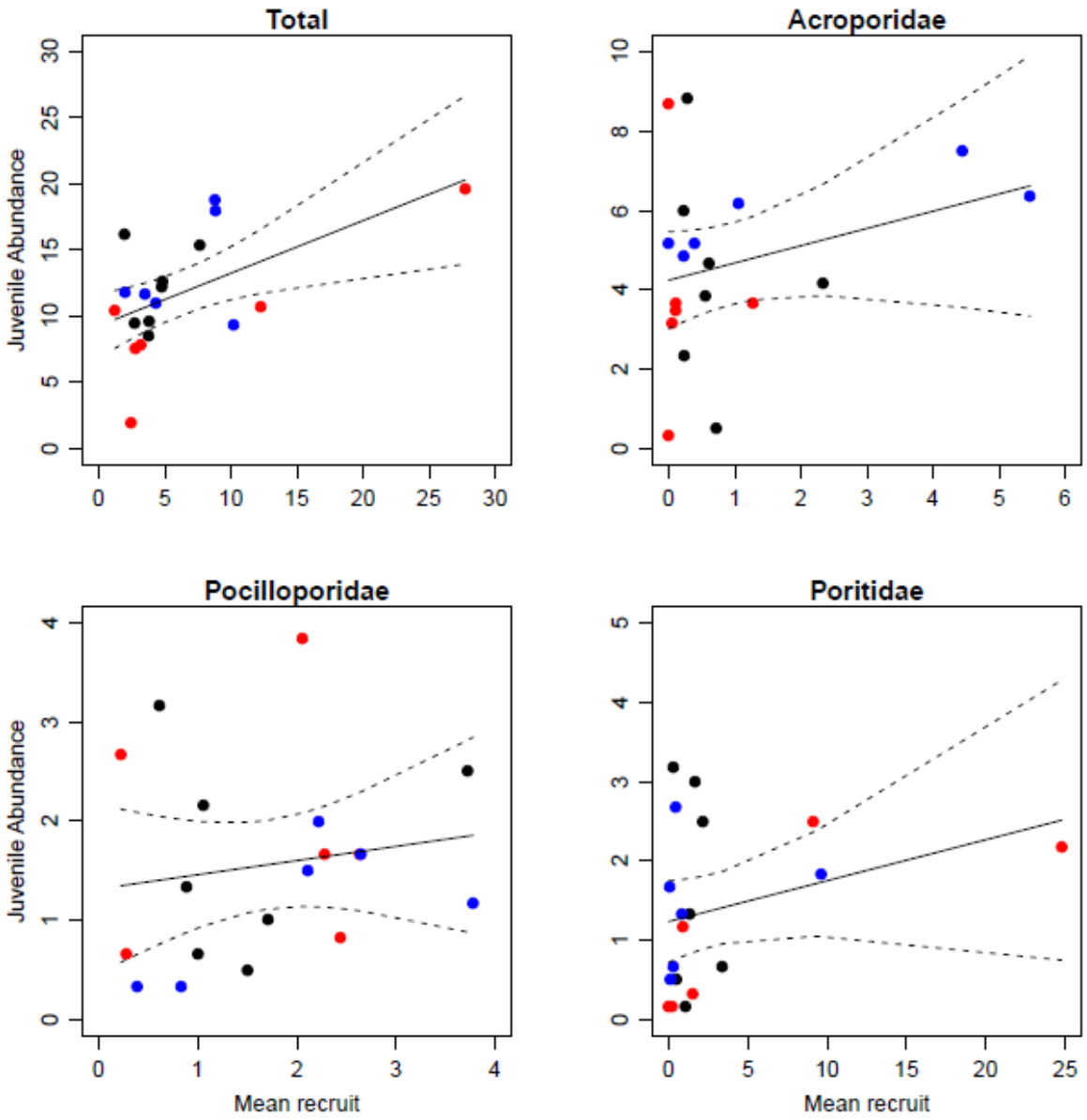


Figure 3.25. Stock recruitment relationship – comparing mean number of recruits (on 2011 recruitment survey tiles) to mean abundance of juvenile corals at each location in 2011. Points are observed values, solid line is the mean predicted fit from GAM and dash lines are 95% confidence intervals. Colours indicate the four study reefs. a) Total recruits (all families) and total juvenile abundance (mean juvenile corals per transect), b) Acroporidae recruits and juveniles, c) Pocilloporidae recruits and juveniles, d) Poritidae recruits and juveniles.

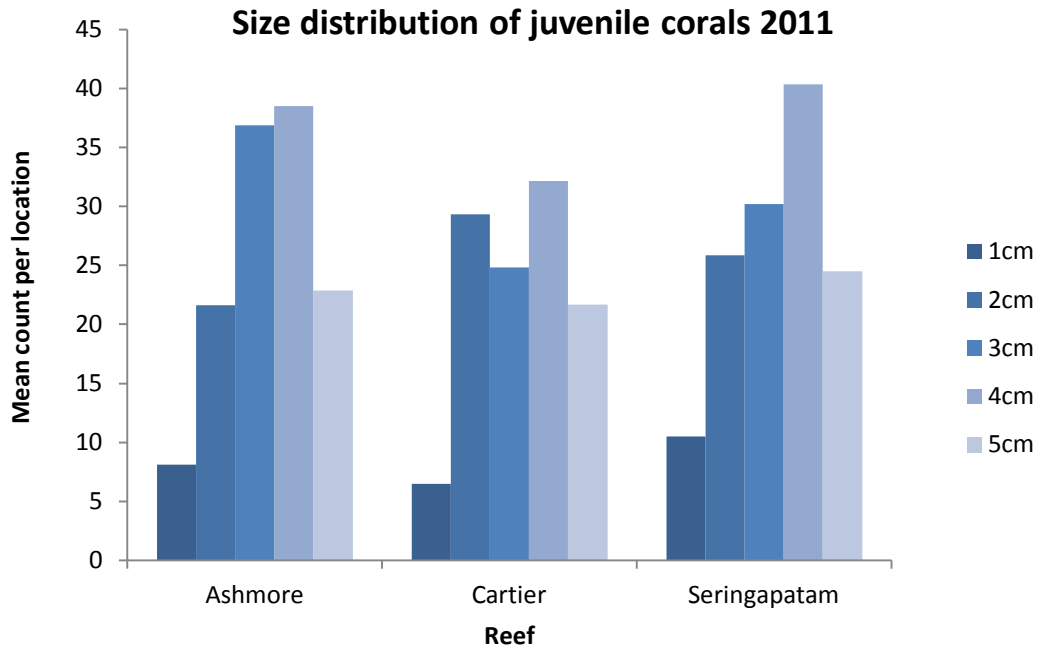


Figure 3.26. The size distribution of juvenile corals, measured to the nearest centimetre, for each of the main survey reefs Ashmore, Cartier and Seringapatam in 2011 (all families combined).

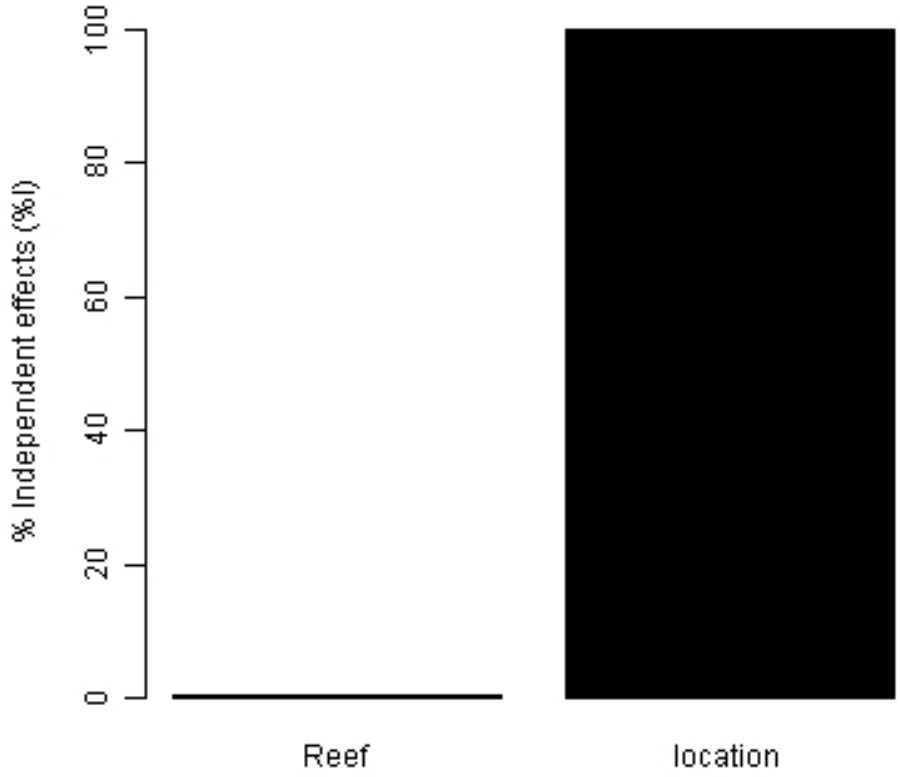
Table 3.15. Generalized additive model (GAM) results investigating the stock-recruitment relationship –for the relationship between mean juvenile coral abundance to mean number of recruits per survey tile at each location in 2011.

	Edf	Ref.df	F	P
Total	1.000	1.000	7.525	**0.014**
Acroporidae	1.000	1.000	1.525	0.234
Pocilloporidae	1.000	1.000	0.434	0.519
Poritidae	1.000	1.000	1.658	0.215

Table 3.16. Permutation test for hierarchical partitioning of juvenile abundance in 2010 and 2011 contributed by reef and site.

		Obs	Z score	Significant (95%CI)
2010	Reef	0.07	3.30	*
	Site	0.47	7.16	*
2011	Reef	0.00	-0.94	
	Site	0.68	12.62	*

a) 2010



b) 2011

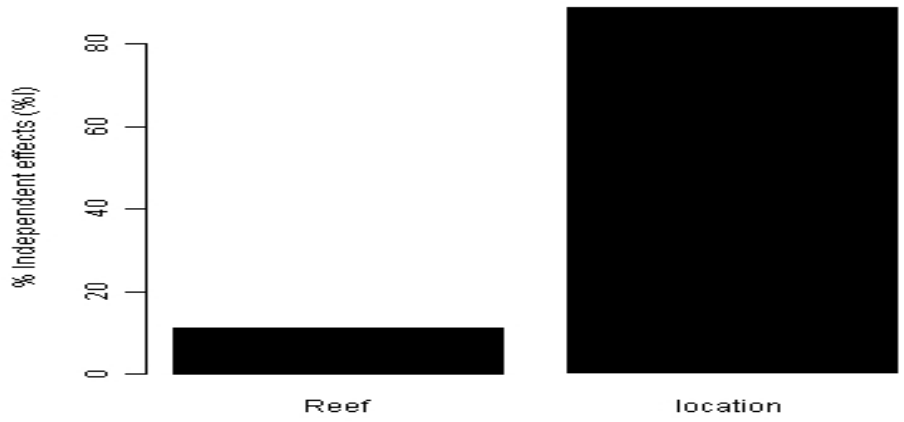


Figure 3.27. Hierarchical Partitioning of Variance of Juvenile coral abundance at the surveyed reefs for each of the independent effects Reef and Site.

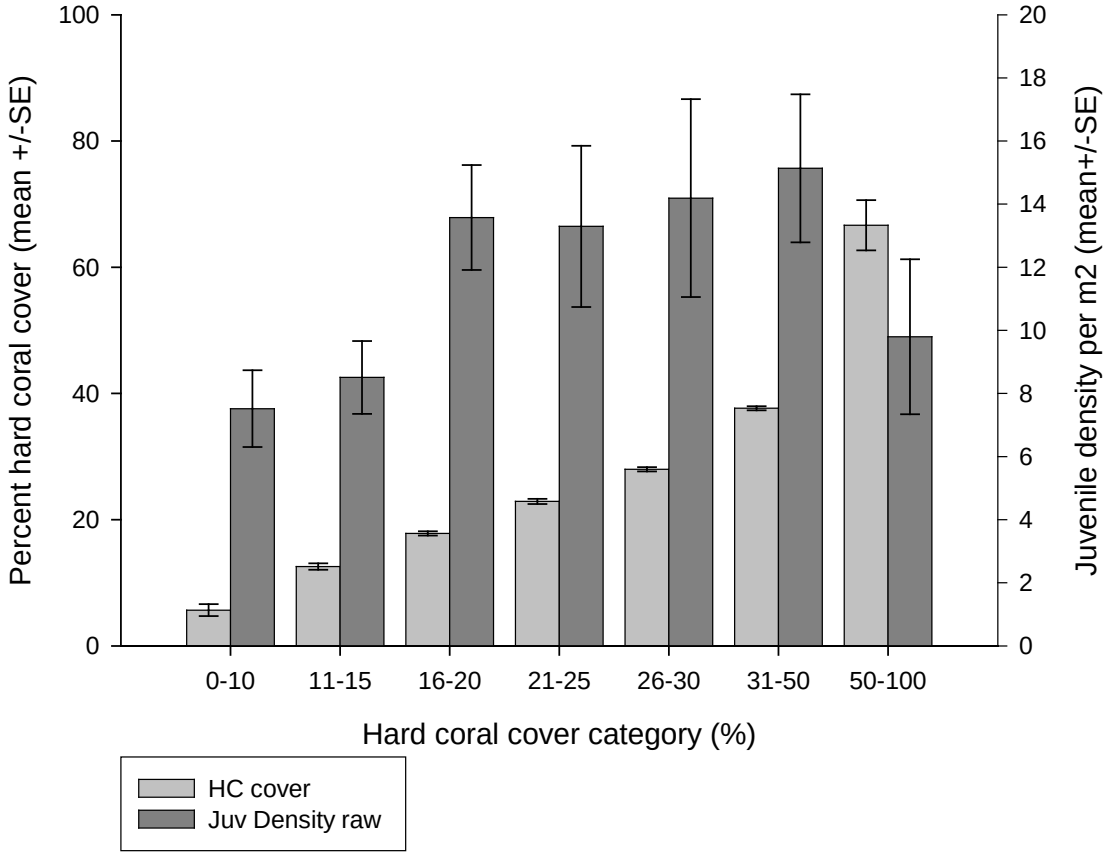


Figure 3.28. Mean adult hard coral cover (±SE)for reefs grouped into hard coral cover categories, with corresponding mean juvenile densities (number of juvenile hard coral colonies per m^2).

3.4 Conclusions

3.4.1 Gonad condition analysis

The analysis of coral samples for gonad condition provides valuable new insights into coral reproduction in the Ashmore Reef and Cartier Islet marine reserves. High levels of gametogenesis are taking place, with developing or mature gonads found in all but a few species.

The timing of spawning at these reefs is yet to be comprehensively observed, but inference from the gonad condition indices point to likely broadcast spawning periods in spring and autumn. However our sampling shows that in 2011, there was broadcast spawning likely following full moons in mid September, February and March. The September spawning for multiple species in at least the Acroporidae and Faviidae is one month earlier than seen on more southern reefs, such as Scott Reef and the Rowley Shoals (Gilmour et al. 2009, Heyward, pers. obs). Consequently, the regional spawning synchrony may be a more complex one than the available literature suggests. These results are also consistent with the preliminary observations made at Ashmore Reef in 2010 (Heyward et al. 2010), where very little evidence of corals with mature gonads was found in the first week of April. This result left open the question of whether the Montara uncontrolled release had possibly inhibited coral reproduction, these new results favour the interpretation that in 2010 most spawning had occurred in February or March prior to the sampling in early April. The exact timing of major coral spawning at these reefs is not known, but the vestigial spawning observed for a single species, Favites abdita, on 6thApril 2010, is consistent with lunar related timing for more southern reefs on the NW Shelf, which tend to spawn 8-9 nights after the full moon.

While broadcast spawning species make up the majority of common reef building corals at these reefs, a number of brooding species can be common and important components of the coral community. These include *Acropora palifera, Pocillopora damicornis, Pocillopora verrucosa, Seriatopora hystrix* and *Stylophora pistillata*. Histological examination of these species revealed gametes in most developmental stages. Planulae were present in some autumn samples of *Acropora palifera, Pocillopora damicornis* and *Seriatopora hystrix*. Planulae were most commonly present when the eggs and testes were still at immature egg stages. Consequently, while this provides clear evidence that these important brooding species are also reproductively active, it is unclear when planulation occurs, however, it is conceivable there are sequential planulae releases over protracted seasonal periods. Some brooding coral species have been known to spawn outside of the typical broadcast spawning period in the broader offshore NW region (Gilmour et al. 2011).

The high levels of gametogenic activity seen in most species during the autumn and spring spawning periods confirms that reproduction is occurring on Ashmore, Cartier and Seringapatam reefs following the 2009 Montara uncontrolled release. The presence of juvenile corals indicates survival of recruits at all reefs and the numbers are normal. There are significant differences in gamete condition within and between reefs for many species, but there is no clear pattern that points to a consistent difference between the two reefs closest to the uncontrolled release and the far removed control reef. For example, observations of smaller egg size or fecundity at Ashmore Reef for some species are countered by opposite trends or neutral results for other species. Uncertainties remain about the timing and the degree of interspecific synchrony of spawning within and between these three reefs. In relation to fecundity and gamete development, notwithstanding the limitations of the study's sampling intensity, there is no clear pattern that would indicate some sort of gradient response to the Montara uncontrolled release. In particular, a lack of baseline data on these processes in the marine reserves, especially over a long enough timeframe to characterise natural variability in these processes, makes it difficult to determine whether egg size and count has been affected.

3.4.2 Recruitment

Based on the analysis of gamete activity, the deployment and recovery period used in this study would have enabled the tiles to sample settling coral recruits from a significant number of broadcast spawning species following either February or March full moons. As planulae were detected in a number of brooding species, it is also likely they would be settling on the reef during the deployment period. The composition and mean number of recruits per tile is very similar between Ashmore, Cartier and Seringapatam Reefs, providing no evidence that recruitment is abnormally low at Ashmore and Cartier following the Montara uncontrolled release. The overall levels of recruits per tile at these three reefs are lower in comparison to some other studies, such as on the central GBR (e.g. Sammarco and Andrews, 1988) but in the same range as recorded for Indian Ocean Reefs including recent sampling with identical methods at Ningaloo (Depczynski et al. 2011 and references therein). The higher general levels of recruitment at Scott Reef, and the markedly higher numbers of broadcast spawning Acroporidae there, are most likely explained by variations in abundance of Acroporidae, local hydrodynamics and the likelihood that these reefs are highly reliant on self seeding (Underwood et al. 2009; Gilmour et al. 2009). The greater levels of recruitment at Scott Reef in comparison to the three main study reefs may also reflect their different disturbance histories. Scott Reef suffered a major loss of live coral and subsequent dramatic decline in recruitment following the 1998 global bleaching event (Smith et al. 2008), followed by both widespread and localised cyclone impacts, however, coral cover, recruitment and community structure has subsequently been steadily increasing. AIMS long-term monitoring of Scott Reef has tracked changes in coral cover and recruitment since 1994, demonstrating this decline then recovery. It is notable that in the immediate years post-disturbance coral recruitment, measured using tiles as in the present study, was very low and after 5 years remained <2% of previous levels (Gilmour et al. in prep.), but in subsequent years recruitment and post-recruitment growth have dramatically increased to essentially a full recovery after 12 years. Given Ashmore is reported to have suffered a similar loss of coral through bleaching between 2000-2003 (Rees et al. 2003, cited in Ceccarelli et al. 2011), recruitment may be at intermediate levels and, if these reefs follow a similar trajectory to Scott Reef, be expected to continue to increase. In this scenario, continued growth of corals at Ashmore should be associated with relative increases in coral recruitment over coming years.

Recruitment was highly variable at all spatial scales studied, but particularly with regard to location on individual reefs. Recruitment of corals and other marine organisms with planktonic larvae, is characteristically variable at all spatial scales (Baird, 1997). Broad and fine scale oceanographic patterns play a major role in determining larval distribution and gene flow within and between reefs (see Underwood et al. 2009). At the location level, the strongest stock recruitment relationship was seen for Pocilloporidae. The common Pocilloporidae species at the studied reefs brood planulae larvae internally. Brooding coral larvae are ready to settle quickly, and while capable of surviving long periods in the water column, are often found to recruit close to natal populations (Best, 1987; Richmond, 1987; Carlon, 1993). Numerous studies have found consistency in spatial patterns of recruitment for brooding corals in relation to highest densities of adults, and genetic population structure at smaller scales than broadcast spawning species (Nishikawa, 2003; Miller, 2008; Underwood, 2007). The number of Pocilloporidae recruits seen on recruitment tiles in this study was relatively low compared to other taxa, however, these species are known to spread their reproductive effort over numerous months of the year (Harrison, 1990; Richmond, 1990; Tanner, 1996; Fan, 2006). This relationship is consistent with an earlier genetic study on Scott Reef showing that most larvae of the brooding Pocilloporid *Seriatopora hystrix,* recruit within 100 m of their natal reef area (Underwood, 2007).

There were some limitations with regard to interpreting the recruitment sampled with the deployed tiles. Due to the duration of the tile deployment, we had limited ability to confidently separate

Isoporan recruits from the other Acroporids. Isoporan recruits are larger than other Acroporid recruits of the same age during early development (0-2 months) (Babcock, 2003), however, this distinguishing feature is less useful when the age of the recruits cannot be ascertained. In order to quantify the entire recruitment effort for the poorly defined autumn mass spawning period, the recruitment tiles were left out for three months to capture a bimodal spawning. The tiles therefore had spawning *Acropora* recruits from at least two cohorts approximately a month apart, and brooding Isoporan recruits which may have settled throughout the deployment period. It is likely that a number of the younger Isoporan recruits were not distinguished from the older *Acropora* cohort.

3.4.3 Juvenile Corals

The patterns of juvenile coral abundance were found to be very similar between Ashmore, Cartier and Seringapatam Reefs, as was the case for newly settling coral recruits. These data suggest that very similar processes of recruitment and post-settlement survival are operating at these reefs. The numbers of recruits are comparable with reefs supporting similar levels of spawning coral stock on the GBR. Overall the patterns look normal and the two reefs closest to the Montara uncontrolled release (Ashmore and Cartier) do not show anything unusual in relation to juvenile coral abundance.

Mean abundance of juvenile corals for the two locations studied at Scott Reef in 2010 (25.8 ± 5.5 SE) was significantly higher than all other studied reefs (Table 3.9, Figure 3.21) and based on other AIMS studies at Scott Reef may be a relatively consistent pattern. The high abundance of Acroporidae juveniles at Scott Reef may indicate that this reef has received high numbers of Acroporidae recruits in the past few years and/or that post settlement survival of Acroporidae recruits is high at this reef. In either case the abundance of recruits and small corals at Scott Reef, relative to the three main reefs surveyed in this study, may reflect its greater size, more fecund spawning stock due to a longer time since reef wide disturbance, and more complex local oceanography that may favour greater retention of larvae.

Based on the similarity of recruitment and juvenile abundance at Ashmore, Cartier and Seringapatam Reefs, combined with evidence of widespread coral gametogenesis and spawning activity, it would be expected that coral abundance and juvenile recruitment will continue to increase over coming years unless a significant disturbance occurs.

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4. CORAL REEF FISH ASSESSMENT

4.1 Introduction/background

For forty-five days from 21st August 2009, there was an uncontrolled release of oil from the Montara Well Head Platform (MWHP) into the ocean on the North-West Shelf marine biogeographic province off the North-west coast of Australia. This occurred during a period when many tropical reef fishes spawn and their buoyant eggs and pelagic larvae may have been exposed to oil pollution. Oiled seawater contains toxic compounds such as polycyclic aromatic compounds (PAHs) that can cause physical deformities in fishes and alter their natural development (Fodrie & Heck 2011) and previous studies have shown its effects to include premature spawning and decreased survival of eggs, altered timing of development of eggs and larvae (Loya & Rinkevich 1980, Tuvikene 1995, Fodrie & Heck 2011) and increases in sub-lethal larval deformities (Kocan et al. 1996). Such detrimental effects can occur at very low levels (*ca* 1 ppb PAHs) of exposure when persistent over days to weeks (Brown et al. 1996, Carls et al. 1999). Although some studies have investigated the effects of oil spills on coral communities on tropical reefs (Johannes 1975, Loya & Rinkevich 1980, Bak 1987, Jackson et al. 1989, Guzman et al. 1991), there have been few similar studies on reef fishes.

The aim of this study was to determine if there were any patterns in the size, abundance and composition of fish communities on reefs near to the Montara well head that were consistent with impacts from the uncontrolled release. Our study reefs were a remote group of shelf-edge atolls in the Indian Ocean between Timor and the north-west coast of Australia (Figure 1.1) that have a diverse array of flora and fauna (Bryce et al. 2009) and low levels of human impacts and thus are high priorities for conservation. These reef systems are located in a zone of regular cyclonic activity, suggesting that they have evolved over thousands of years to withstand and recover from natural episodes of disturbance (Moberg & Folke 1999). To some extent, the resilience of reef fish faunas to recover from acute disturbance will depend on the connectivity of reef systems, as this will allow new individuals to be supplied from reefs unaffected by local disturbances (e.g. Williams & Speare 2002, Halford et al. 2004). Evidence from Scott Reef, immediately to the south of the study region, provided by molecular analyses of fishes and corals indicates that genetic exchange with its neighbouring systems occurs only sporadically and there may be intervals of years, decades, or even longer periods between inputs of exogenous larvae into reef populations (Underwood et al. 2009, Underwood et al. in press). This genetic data implies that isolated reef communities in this region rely on their own reproductive output to respond to disturbance events and that as a consequence, they may be less resilient than reefs within an inter-connected, archipelagic system such as the Great Barrier Reef.

To address whether there were any negative impacts of the Montara uncontrolled release on shallow reef fish communities, the current monitoring program recorded the densities, biomass and lengths of reef fishes at two reefs within the proximity of the release, and at one reef much further away. It was hypothesised that if there were detrimental impacts to either the resident fish populations, or fish eggs/larvae, then such impacts would be evident as conspicuously low densities/biomass of particular groups of fish and/or a reduced contribution of the smaller size classes of fish to the assemblage as a whole.

4.2 Methods

4.2.1 Fish surveys

Fish surveys were conducted in March 2011 using underwater visual census (UVC) and diver operated stereo video (DOV) techniques along the same 20 m transects used for the benthic study described previously (see section 2.2). Thus, for the analysis of both fish and benthic communities there were six replicates (transects) for each of two depths (3 m and 6 m) at each location at each reef in 2011. Note that data for fish were not collected during the 2010 monitoring survey. For UVC, the fish species encountered on each transect were recorded by a diver on SCUBA who identified and counted the number of fishes belonging to all diurnally active, non-cryptic fish families (Figure 4.1A). Larger, more mobile species were surveyed first along a 5 m corridor of the transect, while the smaller, more site attached damselfishes were surveyed along a return pass of the transect within a 1 m corridor. A second diver carried the stereo DOV unit and swam side-by-side with the UVC diver recording video footage of each transect for subsequent analysis in the laboratory.

The stereo DOV technique used two video cameras in underwater housings mounted 0.7 m apart on a base bar and at an angle that inwardly converged at 8 degrees (Figure 4.1B). The cameras were Canon HF S21 digital video cameras that recorded on progressive scan. The system had a synchronising diode mounted in front of the cameras and floats attached to the base bar to make it neutrally buoyant in the water. The system was designed by SeaGis Pty Ltd in Australia and has been used to survey reef fish communities elsewhere in Western Australia (Watson et al. 2005, Watson et al. 2010).

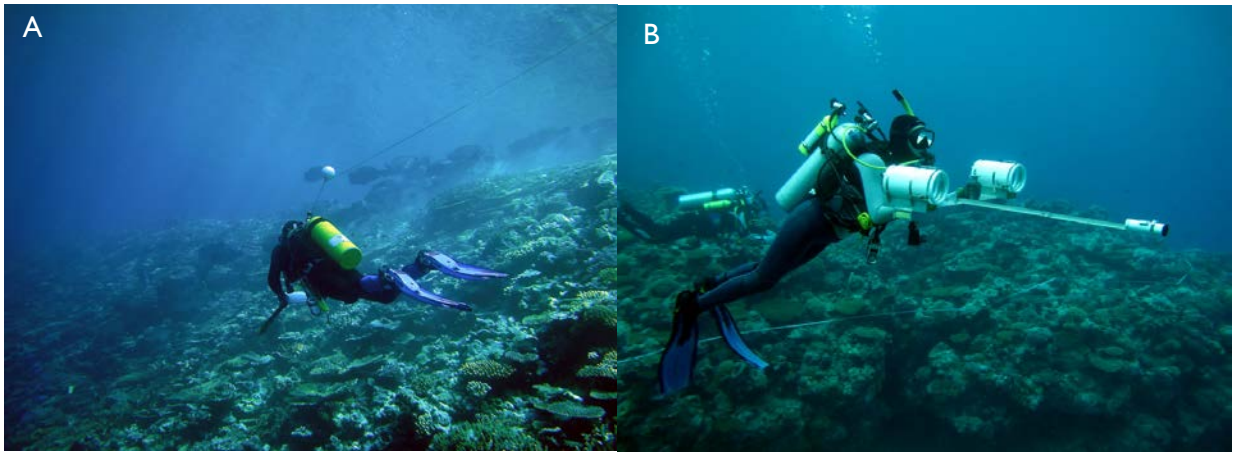

Figure 4.1. Methods used to census reef fishes during the current study. (A) Underwater visual census (UVC) and (B) stereo diver operated video (DOV).

For UVC analyses, abundances of fishes were converted to densities (number of fish, 100 m^{-2}) to account for the differences in transect width for counts of damselfishes (1 m) and all other fishes (5 m). The total number of species, density of each individual fish species and the total density of fishes on each transect was calculated. For DOV analyses, the program EventMeasure (SeaGIS Pty Ltd) was used to identify and enumerate all fish species encountered along the 5 m and 1 m widths of the belt transect for the larger mobile and smaller territorial species, respectively, and to estimate their total length (TL) measurements from stereo-video image pairs. Lengths of individual fishes were converted to weight using species specific allometric length–weight relationships derived from the FishBase online database (Froese & Pauly 2009). The product of individual weights and numerical

densities was used to estimate the biomass of each species and also the total biomass along each transect.

Fish species were classified into seven trophic groups based on their diet and feeding behaviour. Species classified as corallivores included both obligate and facultative coral feeders (Pratchett 2005, Wilson et al. 2006). Herbivorous species were identified as by Green & Bellwood (2009) while detritivores (including epilithic algal matrix feeders), spongivores, planktivores, omnivores and carnivores followed Froese & Pauly (2009) and Wilson et al. (2003).

Additional abundance data of fishes was integrated into the present study from previous surveys of outer reef slope habitats (6 m) at Scott Reef and the Rowley Shoals, two isolated reef systems to the south of the present study area and thus with a comparable ichthyofaunal assemblage. While these surveys were conducted within the same time period (late 2010 to early 2011), they were derived from counts along transects of much longer length within a different experimental design. Thus, to enable broad comparisons of the fish fauna among the present and previous datasets, densities were converted to percentage contributions.

4.2.2 Statistical analyses

The species richness (total number of fish species per transect), biomass and density of fishes were analysed among reefs, depths and sites using 3-way ANOVA's with the factor site being nested within the factor reef. In order for data among outer slope sites to be comparable, the two lagoon sites at Ashmore Reef (A71 and A72) were excluded from this analysis. To meet the assumptions of normality and homoscedasticity, species richness and biomass were square root transformed and density was $\log_e(10)$ transformed. The relationship between the $\log_{10}$ of the standard deviations and $\log_{10}$ of the means of the densities and biomass of each fish species and the number of species demonstrated that this was an appropriate transformation (Clarke & Warwick 2001). Analyses used the general linear model routines in the statistical program PASW (v. 18.0).

For multivariate analyses, the logarithmic transformation of the fish density data ensured numerous rare species were taken into account and to down-weight the contribution of the more dominant species (Clarke & Warwick 2001). Very rare species, *i.e.* those recorded on only a single occasion, were removed from the analysis resulting in a reduced database composed of 183 species. The Bray-Curtis distance matrix derived from mean transformed values was subjected to non-metric multidimensional scaling (nMDS) ordination. This matrix, and one derived from the percentage cover of the eight main benthic groups, were used for constrained ordination plots using distance-based principal coordinate analysis (PCO) to examine the relationships of fish species and habitat variables (Anderson & Willis 2003, Anderson et al. 2008).

To confirm differences in species composition, Analysis of Similarities (ANOSIM) tests were conducted using a Bray-Curtis similarity matrix constructed from replicate data. For each ANOSIM test, the null hypothesis that there were no significant differences among groups was rejected when the significance level (P) was < 0.05. The extent of any significant differences produced by this test was determined using the *R*-statistic value (Clarke 1993), which can range from +1, *i.e.* all samples within each group are more similar to each other than to any of the samples from other groups, to approximately zero, *i.e.* when the similarities within and between groups are the same. As these ANOSIM tests could hide interactions between the main factors of interest, interactions were also examined using a Permutational Multivariate Analysis of Variance test using 9999 permutations (PERMANOVA; Anderson 2001, McArdle & Anderson 2001), forgoing some of the robustness of the non-parametric approach of ANOSIM for the more penetrative and informative general linear modelling of PERMANOVA. Where testing showed the presence of non-negligible differences, two-way crossed Similarity Percentage analyses (SIMPER: Clarke & Gorley 2006) were used to identify

the fish species that typified the species composition of each *a priori* group and those that were responsible for distinguishing between the compositions in each pair of groups.

The RELATE procedure (Clarke & Gorley 2006) was used to quantify the extent to which the pattern of rank orders between the ichthyofaunal compositions of the various samples in the biotic similarity matrix (derived from the species level density data used in the nMDS ordination analyses) paralleled those in distance matrices constructed at a higher taxonomic level, *i.e.* family and trophic grouping of each species (Somerfield & Clarke 1995). The Spearman rank correlation (ρ) was used to assess the extent to which the multivariate structure of the two matrices agreed.

The relationship between the species composition of reef fish assemblage and the physical and benthic habitat variables was modelled with the multivariate regression based modelling procedure DISTLM (DISTLM: Anderson et al. 2008). A distance-based redundancy analysis (dbRDA) was used to visualise the results of the DISTLM. Percentage contribution of the benthic habitat types were derived from the benthic analyses of transects described in Section 2.2. Two physical variables were used in the model: water depth (3 or 6 m to tide datum) and the aspect (azimuth degrees) of each site, along with the percentage cover of eight benthic groups (hard and soft corals, sponge, abiotic, turf, coralline algae, macroalgae and other). Each habitat variable was square root transformed prior to analysis and there were no auto-correlated variables. The PRIMER v6 multivariate statistics package (Clarke & Gorley 2006) with the PERMANOVA+ for PRIMER add-on module (Anderson et al. 2008) was used for all multivariate analyses.

In terms of the size structure of fishes, we were interested in determining whether a cohort of fish had potentially suffered high mortality after negative interactions of their fish eggs/larvae with oil containing PAHs in the water column during the MWHP uncontrolled release. To this end, we analysed the number of nodes in size-frequency data as a means of determining if a cohort was missing. For this analysis we used Macdonald and Green's (1988) approach that found the best fit for component distributions to histogram data, *i.e.* comparing a single mode, against two modes, three modes, etc., using chi-squared approximation to the likelihood ratio test using grouped data (Macdonald 1987). Size classifications of fishes were computed using *mixdist*, an implementation of the MIX package in R (Macdonald & Green 1988, R Development Core Team 2007, Macdonald & Du 2010). MIX iteratively fits distributions to data based on proportion, mean and standard deviation. The fish length estimates derived from the DOV footage showed that there were two main population components in the samples with the numerous small damselfishes the largest contributor and only a small contribution from the larger, more mobile species. Population differences in length frequencies in these fish communities were investigated in deep and shallow water at each reef and also at the reef level. Mean (± 1SD) lengths were also plotted to illustrate the main differences in fish lengths between depths for selected species and families of fish. Particular focus was on the damselfishes that are fast growing, generally short-lived species (1 to 5 years) as it would take several years before it could be possible to determine whether there was high mortality of a particular cohort in the larger, slow growing and long-lived species.

4.3 Results

4.3.1 Number *of species and abundance of reef fishes*

During the study we recorded a total of 116,110 individuals from 309 species and 29 families (Appendix 4.1). The UVC method recorded a total of 70,280 fishes from 258 species, while DOVs recorded 45,830 fishes from 199 species (Table 4.1). For the UVC data sets, the most speciose families were the damselfishes (Pomacentridae) with 49, wrasses (Labridae) with 44, butterflyfishes (Chaetodontidae) with 32 and surgeonfishes (Acanthuridae) with 24 species (Table 4.2). 88.4% of the individuals were damselfishes (Pomacentridae) and the only other family to make a large contribution

to the numbers were the surgeonfishes (Acanthuridae) that contributed 5.1% of individuals (Table 4.2).

Table 4.1. The total number of fish species and number of fishes recorded by UVC and DOV surveys at Ashmore, Cartier and Seringapatam Reefs in 2011.

Reef	Method	Number of species	Number of families	Number of fish
Ashmore	UVC	194	22	31642
	DOV	147	22	18927
Cartier	UVC	153	22	22235
	DOV	125	20	16641
Seringapatam	UVC	149	22	16403
	DOV	105	19	10262
Total	UVC	258	27	70280
	DOV	199	23	45830

Table 4.2. List of the families of fishes recorded using UVC in 6 m and 3 m depths at three reef systems in north-western Australia and their percentage contributions to total numbers overall and at each reef.

Family	Number of species	Abundance	%	Reef		
				Ashmore	Cartier	Seringapatam
POMACENTRIDAE	49	62120	88.4	28675	19680	13765
ACANTHURIDAE	24	3599	5.1	1434	1138	1027
LABRIDAE	44	1464	2.1	521	517	426
CHAETODONTIDAE	32	778	1.1	316	216	246
SERRANIDAE	15	591	0.8	105	48	438
SCARIDAE	20	435	0.6	168	122	145
LUTJANIDAE	10	338	0.5	160	46	132
CAESIONIDAE	4	291	0.4	2	289	-
POMACANTHIDAE	8	160	0.2	57	73	30
BALISTIDAE	11	111	0.2	28	32	51
ZANCLIDAE	1	87	0.1	46	17	24
MULLIDAE	5	68	0.1	27	16	25
CIRRHITIDAE	3	55	0.1	5	9	41
LETHRINIDAE	4	43	0.1	21	5	17
HAEMULIDAE	5	38	0.1	29	5	4
CARANGIDAE	3	28	< 0.1	20	3	5
NEMIPTERIDAE	3	19	< 0.1	14	2	3
MONACANTHIDAE	4	18	< 0.1	6	8	4
SIGANIDAE	3	12	< 0.1	-	2	10
KYPHOSIDAE	1	6	< 0.1	-	-	6
PSEUDOCHROMIDAE	1	5	< 0.1	2	3	-
MICRODESMIDAE	1	4	< 0.1	4	-	-
EPHIPPIDAE	2	3	< 0.1	-	2	1
TETRAODONTIDAE	2	3	< 0.1	-	2	1
CARCHARHINIDAE	1	2	< 0.1	-	-	2
DIODONTIDAE	1	1	< 0.1	1	-	-
FISTULARIIDAE	1	1	< 0.1	1	-	-
Total	258	70280	100			

Of the numerically dominant damselfishes (Pomacentridae), four species collectively accounted for 60.9% of their total numbers: *Pomacentrus lepidogenys*, *Chromis margaritifer*, *Pomacentrus coelestis* and

Chromis weberi (Table 4.3). Certain species of damselfish showed a pronounced tendency to make greater contributions at some reefs compared to others. For example, while *Pomacentrus lepidogenys* ranked first and third in terms of numbers at Ashmore and Cartier reefs, respectively, it ranked only sixth at Seringapatam (Table 4.3). In contrast, *Chromis margaritifer* was the highest ranked species at Seringapatam where it contributed 43.3% to total numbers, but contributed less than 10% at both Ashmore and Cartier. Furthermore, the damselfish fauna at Cartier Reef was dominated by *Pomacentrus coelestis*, where it contributed 37.5% to the total number of fish, but only 7.5% at Ashmore and as low as 0.5% at Seringapatam (Table 4.3).

Table 4.3. List of the most abundant damselfishes (Pomacentridae) recorded using UVC in 6 m and 3 m depths at three reef systems in north-western Australia. The total number of individuals of each species and their percentage contributions to the total numbers overall, and at each reef are shown. Superscript text indicates ranking within each reef system.

			Reef		
Species	Abundance	%	Ashmore	Cartier	Seringapatam
Pomacentrus lepidogenys	12230	19.7	30.9[1]	13.3[3]	5.4[6]
Chromis margaritifer	9650	15.5	8.4[2]	6.5[4]	43.3[1]
Pomacentrus coelestis	9600	15.5	7.5[4]	37.5[1]	0.5[16]
Chromis weberi	6340	10.2	6.8[5]	15.4[2]	9.8[2]
Pomacentrus philippinus	3520	5.7	4.8[7]	4.2[5]	9.4[3]
Neopomacentrus azysron	3070	4.9	8.3[3]	3.5[7]	-
Chrysiptera rex	2805	4.5	5.6[6]	0.81[4]	7.5[4]
Pomacentrus bankanensis	2155	3.5	3.8[8]	3.0[8]	3.5[9]
Stegastes fasciolatus	1790	2.9	2.4[10]	1.4[11]	6.0[5]
Plectroglyphidodon lacrymatus	1175	1.9	2.3[11]	2.1[10]	0.8[14]
Plectroglyphidodon johnstonianus	1125	1.8	1.9[14]	2.9[9]	< 0.1[22]
Pomacentrus vaiuli	1090	1.8	2.7[9]	0.9[13]	0.9[13]
Plectroglyphidodon dickii	1050	1.7	1.1[18]	1.1[12]	3.7[8]
Abudefduf vaigiensis	765	1.2	0.2[25]	3.5[6]	0.1[20]
Chromis ternatensis	750	1.2	2.2[12]	0.2[21]	0.7[15]
Chromis viridis	715	1.2	2.0[13]	0.7[16]	-
Pomachromis richardsoni	605	1.0	< 0.1[41]	-	4.4[7]
Amblyglyphidodon ternatensis	460	0.7	1.6[15]	-	-
Dascyllus reticulatus	410	0.7	0.5[22]	0.8[15]	0.9[12]
Pomacentrus adelus	370	0.6	1.3[16]	-	-
Total number	62120		28675	19680	13765

The total numbers and percentage contributions of the larger, more mobile fish species that did not belong to the dominant damselfish family are provided in Table 4.4. The roving surgeonfishes *Ctenochaetus* spp., which was comprised exclusively of the morphologically similar *Ctenochaetus strigosus* and *C. striatus*, was the top ranked taxa within this group in terms of both overall numbers and its contribution to the fauna at each of the three reefs (Table 4.4). Some other surgeonfishes (Acanthuridae) also tended to dominate the fish fauna across all reefs with *Acanthurus nigricans*, *A. nigrofuscus* and *A. lineatus* each ranking highly. The abundances of some species, however, were not consistent across reefs. For example, while *Pseudanthias tuka* ranked second at Seringapatam, where it contributed 11.6% to total numbers, contributed less than 1% at both Ashmore and Cartier Reefs (Table 4.4).

ANOVA demonstrated that the species richness and biomass of fishes were significantly related to water depth and site within a reef and density was related to water depth (Table 4.5). There were also significant depth x site interactions for richness and density. Mean square values indicated that most of the variation for each of these three biotic variables was explained by site-level differences within each reef, followed by depth differences in the case of species richness and biomass (Table

4.5). Plots of the data, averaged across sites at each reef, illustrate that the mean number of species and biomass were greater in deep than shallow water at two of the three reefs (Figure 4.2). At a functional level, only the algal-feeding herbivorous species displayed a clear pattern across all reefs, being more abundant in shallow than deep water (Figure 4.2 D-H).

Table 4.4. List of the most abundant larger (non-Pomacentridae) fishes recorded using UVC at 6 m and 3 m depths at three reef systems in north-western Australia. The total number of individuals of each species and their percentage contributions to the total numbers overall and at each reef are presented. Superscript text indicates ranking within each reef system.

			Reef		
Species	Abundance	%	Ashmore	Cartier	Seringapatam
Ctenochaetus spp.	2228	27.3	32.3^{1}	24.0^{1}	24.9^{1}
Acanthurus nigricans	389	4.8	4.1^{3}	4.8^{4}	5.4^{3}
Pseudanthias tuka	347	4.3	0.9^{18}	0.5^{33}	11.6^{2}
Acanthurus nigrofuscus	331	4.1	0.8^{22}	8.8^{2}	3.1^{6}
Acanthurus lineatus	283	3.5	5.2^{2}	2.5^{8}	2.5^{8}
Thalassoma quinquevittatum	220	2.7	1.6^{12}	2.2^{12}	4.4^{4}
Thalassoma amblycephalum	205	2.5	0.8^{21}	4.7^{5}	2.3^{10}
Chlorurus sordidus	197	2.4	2.4^{8}	2.3^{11}	2.5^{9}
Halichoeres margaritaceus	177	2.2	1.9^{11}	0.7^{26}	3.9^{5}
Lutjanus gibbus	150	1.8	3.9^{4}	0.1^{77}	1.2^{18}
Gomphosus varius	146	1.8	2.5^{7}	2.5^{9}	0.3^{46}
Caesio caerulaurea	132	1.6	-	5.2^{3}	-
Thalassoma lunare	130	1.6	2.6^{6}	2.0^{13}	0.1^{73}
Centropyge vrolikii	125	1.5	1.6^{13}	2.5^{10}	0.6^{29}
Chaetodon citrinellus	123	1.5	1.5^{15}	1.4^{16}	1.6^{11}
Thalassoma jansenii	118	1.4	2.4^{9}	1.8^{15}	0.1^{84}
Chaetodon lunulatus	102	1.3	1.9^{10}	0.5^{32}	1.2^{17}
Zanclus cornutus	87	1.1	1.6^{14}	0.7^{28}	0.9^{22}
Chaetodon trifascialis	83	1.0	0.8^{23}	1.9^{14}	0.4^{38}
Caesio teres	80	1.0	0.1^{101}	3.1^{6}	-
Total	8160		2967	2555	2638

Table 4.5. Mean squares (MS), pseudo-*F* ratios and significance level for reef × depth × site (nested) ANOVAs for species richness, biomass and density of fishes. Data for species richness and biomass were square root transformed while density data were $\log_{e}10$ transformed. df = degrees of freedom.

Source	*df*	a. Richness			b. Biomass			c. Density		
		MS	*F*	P	MS	*F*	P	MS	*F*	P
Reef (R)	2	2.9	2.0	0.174	2.4	0.1	0.912	2.9	1.4	0.278
Depth (D)	1	4.1	7.5	**<0.05**	64.4	17.6	**<0.001**	1.9	3.1	0.094
Site (S)[R]	16	1.5	10.9	**<0.001**	24.6	9.5	**<0.001**	2.1	13.6	**<0.001**
R x D	2	1.5	2.8	0.09	2.5	0.7	0.519	0.2	0.3	0.762
D x (S)[R]	16	0.5	3.9	**<0.001**	3.6	1.4	0.144	0.6	4.1	**<0.001**
Residual	190	0.1			2.6			0.1		
Total	227									

Significant P values in bold

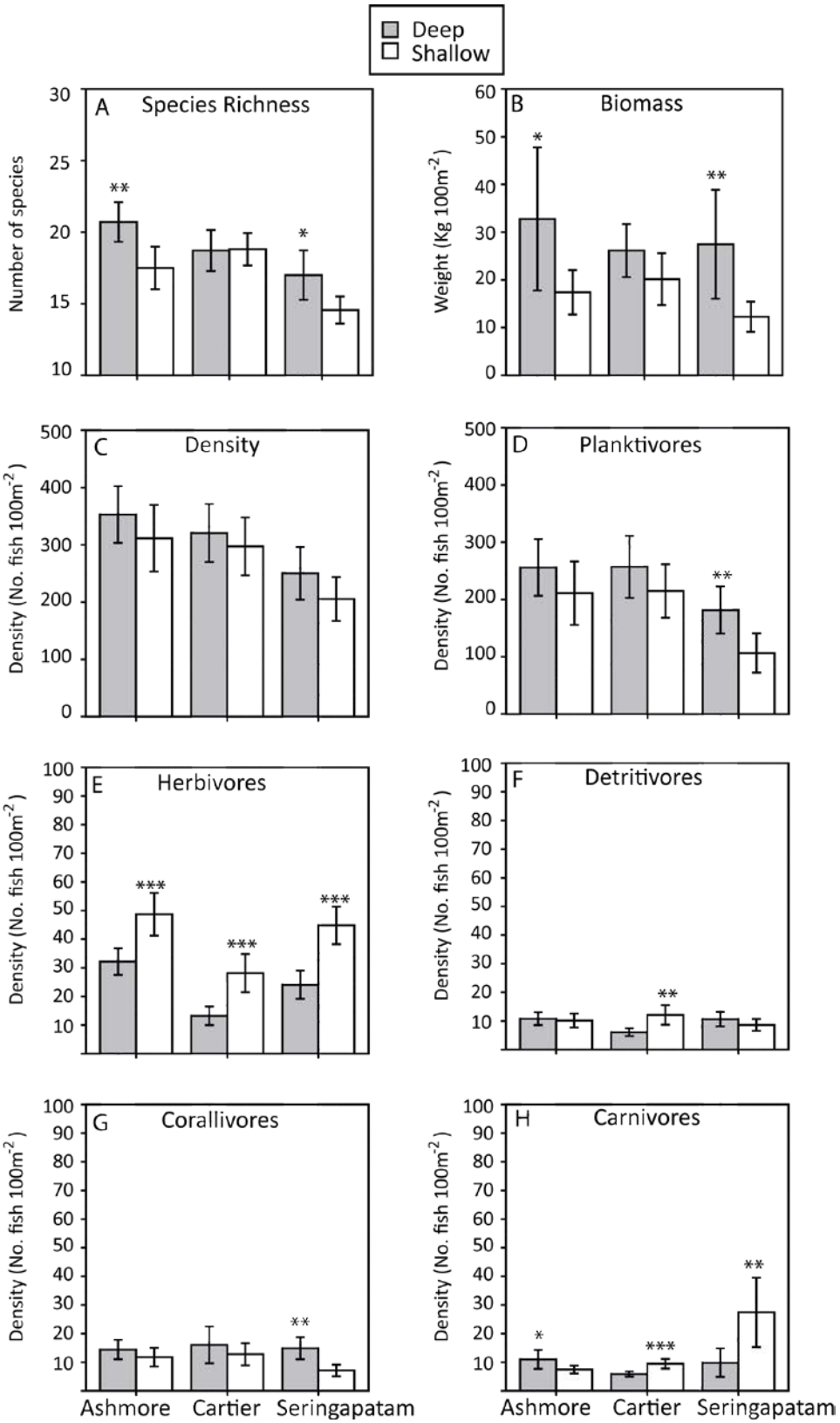

Figure 4.2. Mean number of species, biomass, density of fishes and main functional groups recorded in deep and shallow waters at each of the three reef systems surveyed in 2011. All data in this Figure and Figure 4.3 are derived from UVC except for biomass, which was derived from DOV length estimates. *; $P < 0.05$, **; $P < 0.01$, ***; $P < 0.001$.

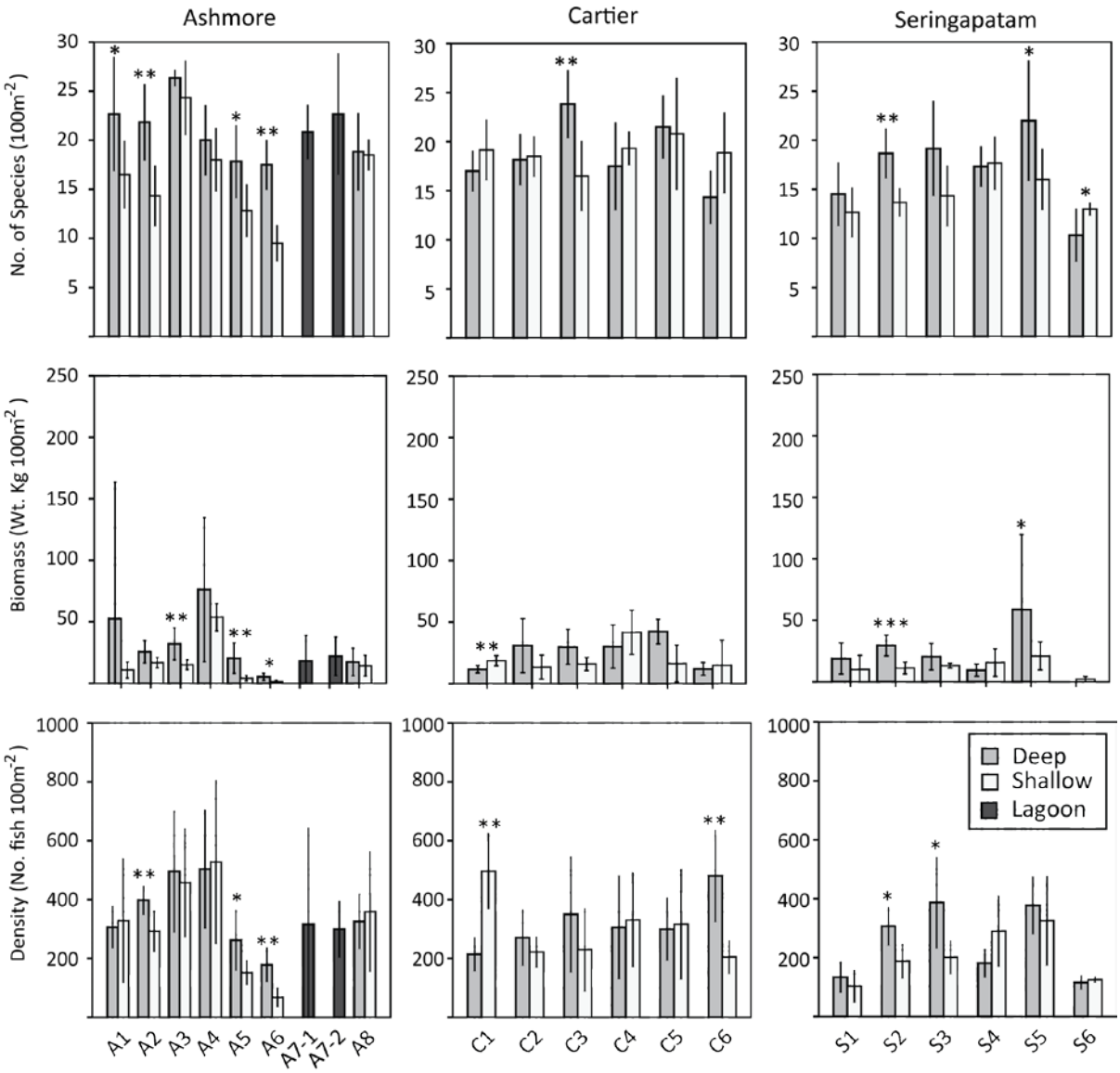

Figure 4.3. Mean number of species, biomass and density of fishes (±SE) recorded by UVC in deep and shallow waters at locations in each of the three reef systems in 2011. *; $P < 0.05$, **; $P < 0.01$, ***; $P < 0.001$.

As there were significant interactions between site and depth, mean values for each of the three main biotic variables were plotted separately for each reef (Figure 4.3). The number of fish species recorded at both Ashmore and Seringapatam Reefs tended to be greater in deep than shallow water, whereas such patterns were not as consistent at Cartier (Figure 4.3). In terms of biomass there were few significant patterns, although there was a trend towards greater biomass at deep than shallow water (Figure 4.3). For density, there were no consistent differences between depths (Figure 4.3).

Planktivores and corallivores tended to be more abundant in deep than shallow water, whereas the reverse was often the case for herbivorous and carnivorous fishes (Figure 4.4), with these differences in abundance between depths being particularly pronounced at sites within Seringapatam Reef. The very high number of planktivores in shallow water at site C1 at Cartier Reef was due to large schools of the planktivorous damselfish *Pomacentrus coelestis*. The highest densities of

carnivorous species were recorded in shallow water at Seringapatam, while corallivores peaked in density in deep water at the two exposed western-most sites at Cartier Reef (C2 and C3, Figure 4.4).

Individuals belonging to the wrasse family (Labridae) were recorded in greater densities in shallow than deep water at Cartier and Seringapatam Reefs, and this was also the case for surgeonfishes (Acanthuridae) at Cartier Reefs (Figure 4.5). In contrast, the coral-feeding butterflyfishes (Chaetodontidae) were recorded in greater densities in deep water at Ashmore and Seringapatam Reefs, while damselfishes (Pomacentridae) displayed no consistent differences in abundance between depths. In terms of differences among sites within reefs, the most notable result was that damselfishes were more abundant at the eastern-most sites at a particular reef than at sites to the west, namely A5 and A6 (west) *vs* A3 and A4 (east) at Ashmore and S1 and S6 (west) *vs* all other sites at Seringapatam (Figures 4.5; 2.1). These spatial differences in numbers suggest that the environment on the western sides of offshore reefs in NW Australia provide habitats less suitable for damselfishes compared with sites on the eastern sides of reefs.

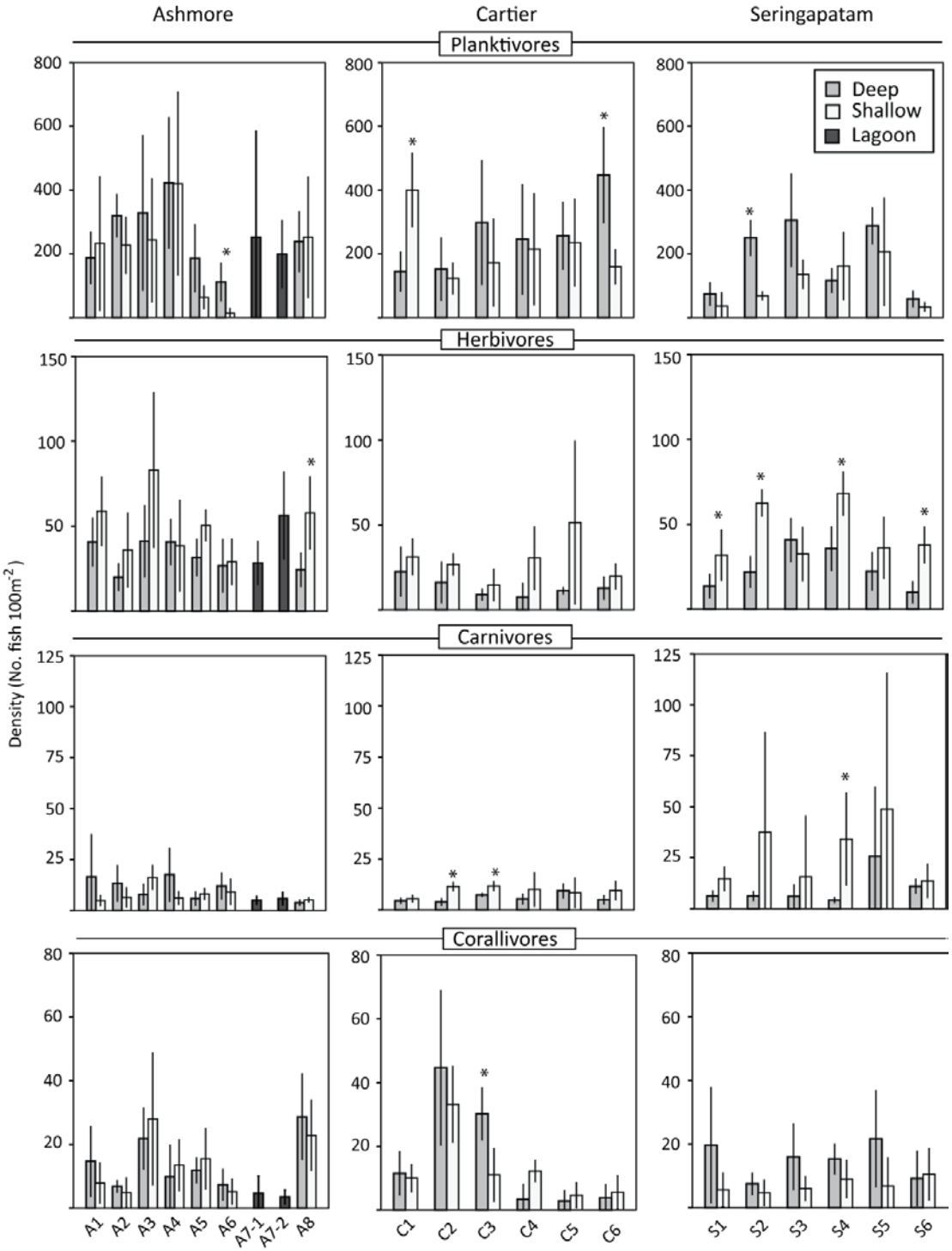

Figure 4.4. Mean densities of the main trophic groups of fishes recorded by UVC in 6 m and 3 m depths at locations in each of the three reef systems in 2011. *; $P < 0.05$, **; $P < 0.01$, ***; $P < 0.001$.

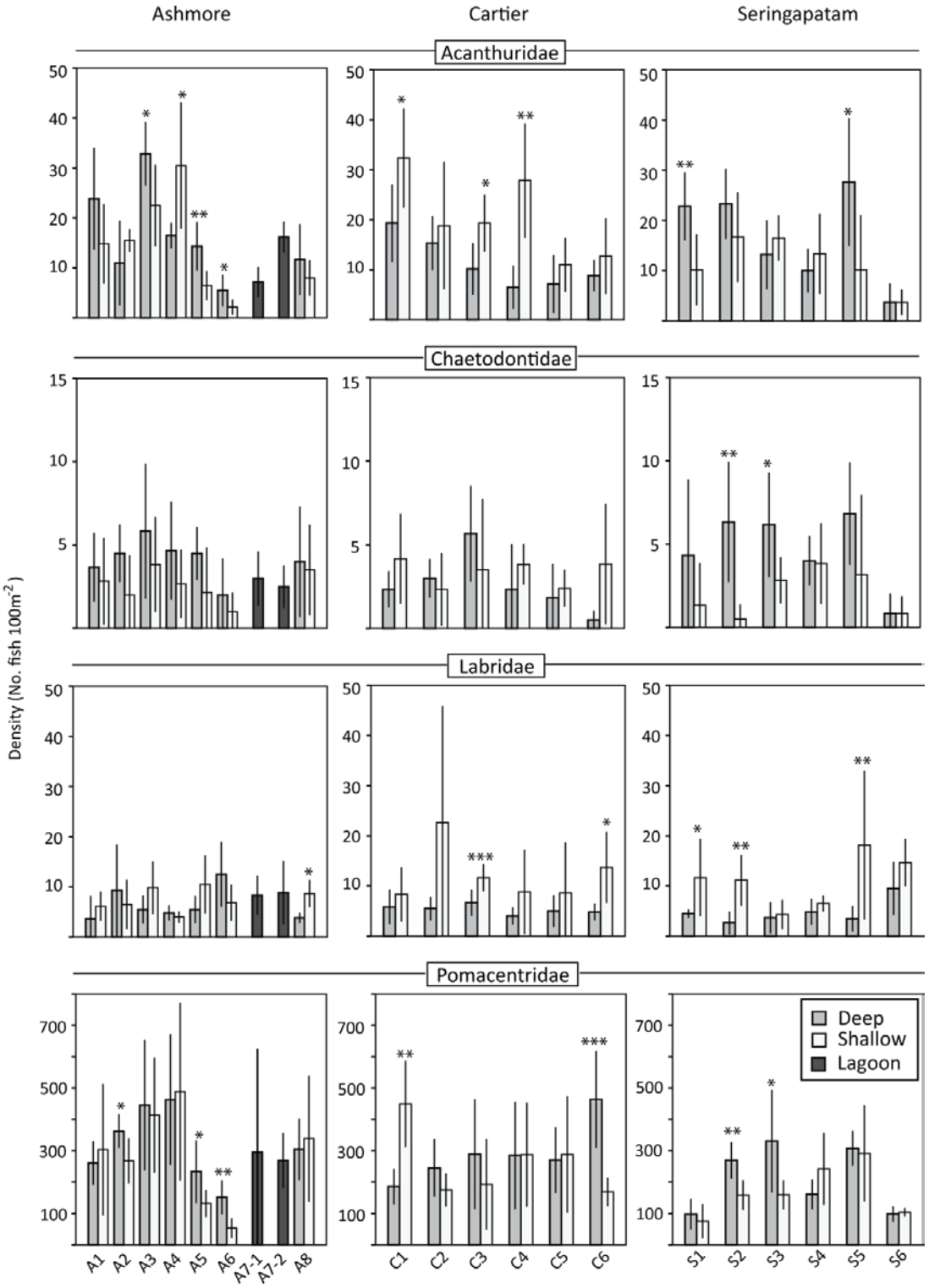

Figure 4.5. Mean densities of the main families of fishes recorded by UVC in deep and shallow waters at locations in each of the three reef systems in 2011. *; $P < 0.05$, **; $P < 0.01$, ***; $P < 0.001$.

4.3.2 Composition of reef fish assemblages

PERMANOVA demonstrated that the species composition of reef fish assemblages was related significantly to reef ($p < 0.01$), depth ($p < 0.001$) and site ($p < 0.01$) within reefs (Table 4.6a). There was also a significant interaction between depth and site. Mean square values indicate that species composition was most strongly related to water depth followed by reef. PERMANOVA also showed that, at the level of family and trophic group, composition differed significantly among depths and sites within reefs, but reef level differences were lost (Table 4.6 b, c).

Table 4.6. Mean squares (MS), pseudo-*F* ratios and significance level for reef × depth × site (nested within reef) PERMANOVA based on the Bray-Curtis dissimilarity measure for $\log_e 10$ transformed density data of (a) all fish species and also for these species classified according to their (b) family and (c) trophic group. df = degrees of freedom.

Source	*df*	**a**. Species			**b.** Family			**c.** Trophic group		
		MS	*F*	P	MS	*F*	P	MS	*F*	P
Reef (R)	2	32551	3.2	**<0.01**	1763	1.1	0.380	3636	1.9	0.067
Depth (D)	1	40501	10.8	**<0.001**	5141	6.3	**<0.01**	5939	7.5	**<0.01**
Site (S)[R]	16	10259	9.7	**<0.01**	1687	6.2	**<0.001**	1852	9.1	**<0.001**
R x D	2	5238	1.4	0.122	1344	1.6	0.105	566	0.7	0.685
D x S [R]	16	3735	3.5	**<0.001**	808	3.0	**<0.001**	785	3.8	**<0.001**
Residual	190	1053			270			203		
Total	227									

R-statistic values from two-way crossed ANOSIM tests for reef and depth showed that the species compositions of each reef differed significantly, with the greatest R values between Seringapatam and either Ashmore (0.356) or Cartier (0.441) than between Ashmore and Cartier (0.199). SIMPER analyses showed that the fish faunas at both Ashmore and Cartier reefs were distinguished from those at Seringapatam by consistently lower densities of the damselfishes *Chromis margaritifer*, *Chrysiptera rex* and *Plectroglyphidodon dickii* and conversely higher numbers of *Pomacentrus coelestis* and *Pomacentrus lepidogenys*. In shallow water, *Stegastes fasciolatus* was also recorded in significantly lower densities at both Ashmore and Cartier compared to Seringapatam Reefs.

Two-way crossed ANOSIM tests confirmed that species composition differed significantly among sites and between depths within each of the three reefs (Table 4.7). R-values emphasised that the magnitude of both site and depth related differences in ichthyofaunal composition were high at each reef and ranged from 0.69 to 0.85. While R- values for site were similar at all reefs (0.69 to 0.78), depth-related differences were greatest at Seringapatam (0.85) and least at Cartier (0.61).

Table 4.7. Global *R*-statistic values and significance levels for depth × site two-way crossed ANOSIM tests, analysed separately for each reef, using UVC data. Significance level: *** $P < 0.001$.

Reef	Site	Depth
Ashmore	0.69***	0.68***
Cartier	0.78***	0.61***
Seringapatam	0.74***	0.85***

Results of PERMANOVA and ANOISM tests suggesting that composition of reef fish assemblages was influenced by reef and water depth were confirmed by the PCO and nMDS ordination plots for each depth and reef, respectively (Figures 4.6, 4.7). PCO plots showed a clear tendency for samples to form groups on the basis of reef, with those for Seringapatam forming a group at the bottom of each plot, and samples from Ashmore and Cartier being arranged across the top (Figure 4.6). The nMDS ordination plots illustrate the influence of both reef and water depth at the species level (Figure 4.7 A & B), whereas this pattern breaks down when data are analysed at the level of family and trophic group (Figure 4.7 C-F).

In the case of deep reefs, those at Ashmore were characterised by greater abundances of the damselfishes *Pomacentrus lepidogenys* and *p. vaiuli*, with Cartier Reef characterised by *Plectroglyphidodon johnstonianus* and *Pomacentrus coelestis* and Seringapatam by greater densities of *Chromis margaritifer*, *Chrysiptera rex* and *Plectroglyphidodon dickii* than the other reefs (Figure 4.6 A). The fish species most strongly associated with the shallow (crest) zone at Ashmore were the damselfish *Chrysiptera hemicyanea*, *Neoglyphidodon nigroris*, *Pomacentrus adelus* and the parrotfishes *Scarus niger* and *Chlororus bleekeri*. Also more abundant in shallow waters, not surprisingly, were species that feed predominantly on algae in the high energy shallow crest zone such as *Thalassoma jansenni* and *Acanthurus nigrofuscus* at Cartier and *Thalassoma quinquevittatum* and *Halichoeres margaritaceus* at Seringapatam Reef (Figure 4.6 B). Additionally, two-way crossed SIMPER analyses for each reef showed that at Ashmore Reef, the fauna in shallow water was distinguished from that in deep water by greater densities and frequency of occurrence of *Pomacentrus bankanensis* and *Pomacentrus coelestis*, whereas the deep water was distinguished by greater densities of *Chromis margaritifer* and *Pomacentrus vaiuli*.

At Cartier, *Pomacentrus bankanensis*, *Ctenochaetus spp* and *Stegastes fasciolatus* were more important in shallow water, whereas the deep water fauna was distinguished by *Pomacentrus lepidogenys* and *Chromis margaritifer*.

At Seringapatam, the damselfish *Stegastes fasciolatus, wrasses Thalassoma quinquevittatum* and *Halichoeres margaritaceus* distinguished the shallow water fauna while the damselfish *Pomacentrus lepidogenys* and *Plectroglyphidodon dickii* distinguished the deep water.

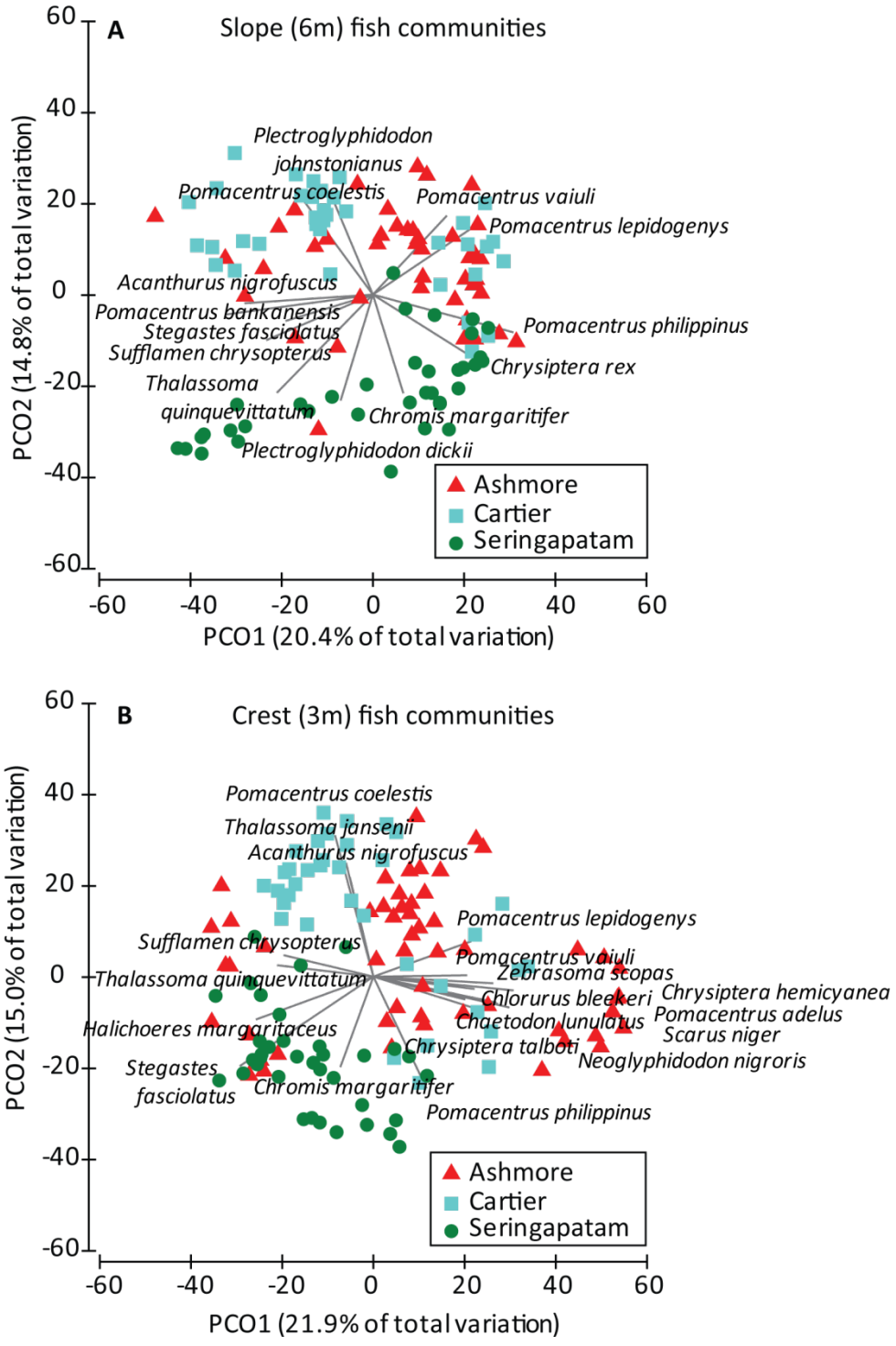

Figure 4.6. Principal coordinate analysis (PCO) of reef fish assemblages associated with (A) 6 m depth and (B) 3 m depths at Ashmore, Cartier and Seringapatam Reefs derived from $\log_{e}10$ transformed density estimates from underwater visual census (UVC). Overlain vectors are species with Pearson correlations >0.4 with the length and direction of the vectors representing the strength of the relationship.

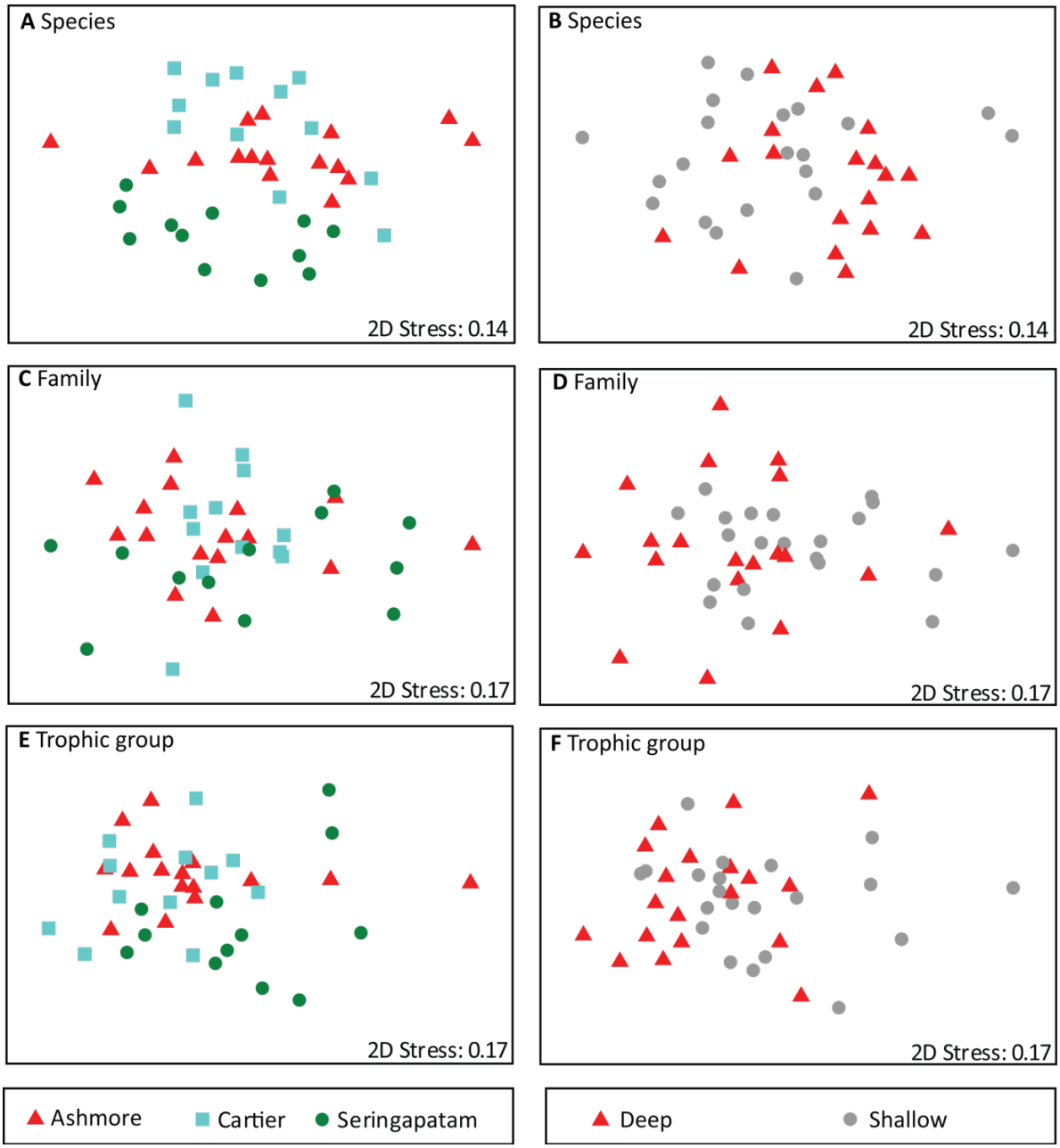

Figure 4.7. nMDS ordination plots showing the separation of samples according to reef and water depth using species level data (A, B) and family and trophic group data (C-F).

RELATE analysis demonstrated that the similarity matrix used to produce the ordination plot in Figure 4.7A was correlated with the distance matrices constructed at both the family ($\rho = 0.49$) and trophic ($\rho = 0.39$) levels. Thus, the pattern of distribution of points shown in the nMDS ordination derived using species data was strongly retained when the multivariate analyses were conducted at level of family and trophic group (Figure 4.7 C-F).

The differences in species composition highlighted in both PCO and SIMPER analyses are illustrated by plots of mean densities of selected species in deep and shallow water habitats at each reef (Figure 4.8). These show that the densities of the damselfishes *Pomacentrus coelestis* and *P. lepidogenys* were greater at Ashmore and Cartier, whereas those of *Chromis margaritifer* and *Plectroglyphidodon dickii* were much greater at Seringapatam. Densities of *Plectroglyphidodon johnstonianus* were also conspicuously low at Seringapatam compared with Ashmore and Cartier Reefs.

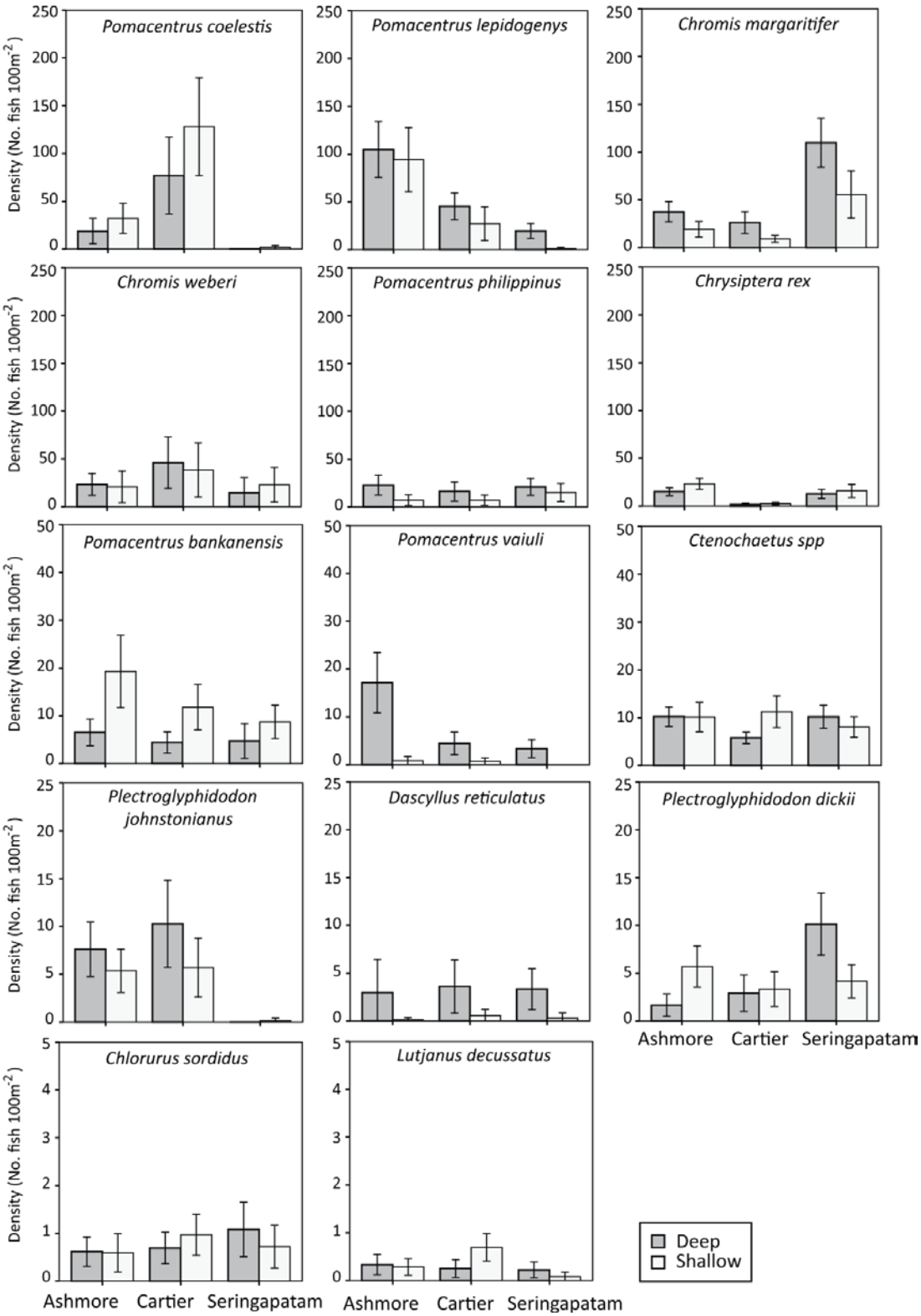

Figure 4.8. Mean densities of fishes identified by SIMPER analyses as being diagnostic of certain reefs or water depths.

4.3.3 Relationship between fish and benthic composition

The distance-based modelling routine DISTLM demonstrated that physical (aspect and water depth) and habitat variables (eight benthic groups) each explained 17.7% of variation in fish assemblages and together accounted for 31.1% of total variation in fish abundance (Table 4.8). The greatest amount of variance was explained by aspect (10.1%), followed by water depth (7.6%) and cover of soft and hard corals which each explained 2.5%. Remaining habitat variables also contributed a small, but significant component.

Figure 4.9 shows the results of the DISTLM routine using distance based RDA (dbRDA) overlaid with the partial correlations of the significant physical and environmental variables. This plot highlights that sites with a northern or eastern aspect largely grouped on the right of the plot, whereas those with a south or western aspect grouped to the left. When the dbRDA plot was coded according to the percentage contribution of the two main habitat variables identified by DISTLM, there were clear gradients along the first axis, with soft coral increasing in cover at sites with a northerly aspect, in contrast to sponge cover that increased to the left of the axis at sites with more southern or western aspects (Figure 4.10 A, B).

Table 4.8. Results of distance based multivariate regression modelling (DISTLM) of species data on physical and benthic category variables at Ashmore, Cartier and Seringapatam Reefs for (a) each variable taken individually (ignoring other variables) and (b) forward-selection of variables, where amount explained by each variable added to model is conditional on variables already in the model (*i.e.* those variables listed above it). %Var: percentage of variance in species data explained by that variable; Cum. %: cumulative percentage of variance explained.

Variable	%Var	*F*	p	Cum. (%)
(a) Variables fitted individually				
Aspect	10.1	25.4	**0.001**	
Depth	7.6	18.6	**0.001**	
Turf	4.8	11.5	**0.001**	
Soft coral	4.1	9.7	**0.001**	
Hard coral	2.6	6.2	**0.001**	
Sponge	2.4	5.5	**0.001**	
Abiotic	2.3	5.4	**0.001**	
Macroalgae	1.9	4.5	**0.001**	
Coralline	1.5	3.4	**0.001**	
Other	1.2	2.9	**0.01**	
(b) Variables fitted sequentially				
Aspect	10.1	25.4	**0.001**	10.1
Depth	7.6	20.8	**0.001**	17.7
Soft coral	2.5	7.1	**0.001**	20.2
Hard coral	2.5	7.2	**0.001**	22.7
Abiotic	2.1	6.3	**0.001**	24.9
Turf	2.0	6.2	**0.001**	26.9
Sponge	1.3	3.9	**0.001**	28.2
Macroalgae	1.1	3.4	**0.001**	29.3
Coralline algae	1.1	3.4	**0.001**	30.4
Other	0.7	2.3	**0.01**	31.1
Significant values in bold				

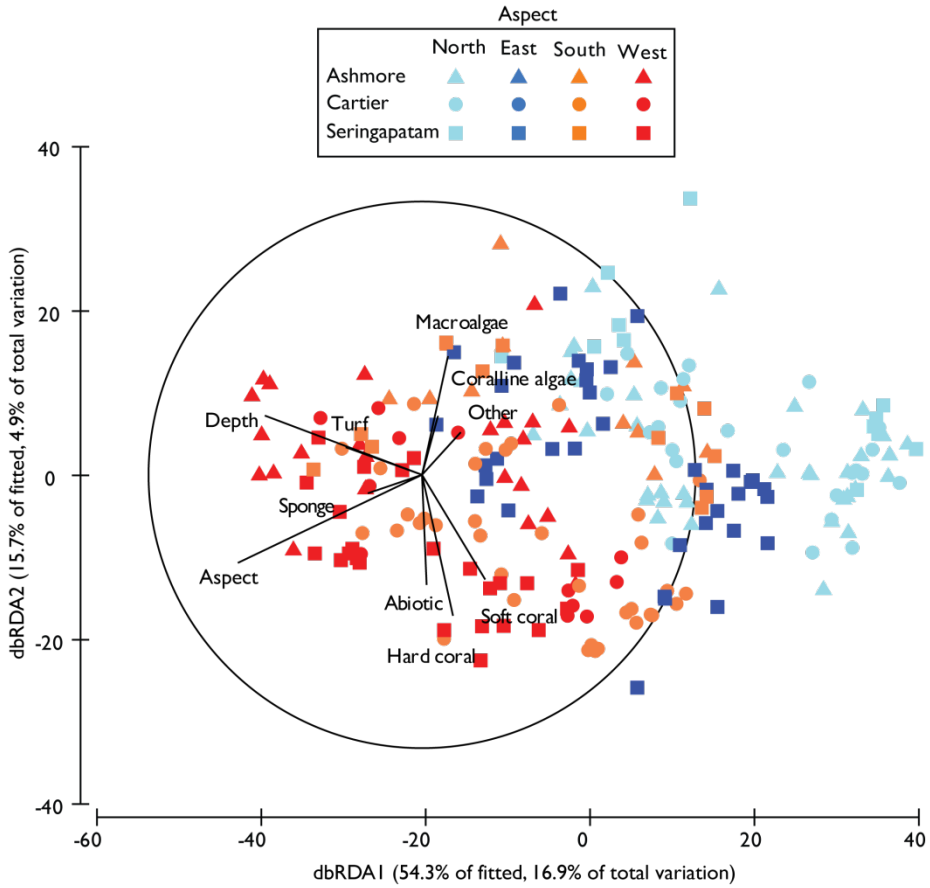

Figure 4.9. Distance based RDA plot (dbRDA) ordination plot for the fitted multivariate regression model (DISTLM) of the reef fish assemblages overlaid with the partial correlations of the significant physical and environmental variables. The length and direction of the vectors represent the strength and direction of the relationship with samples coded according to aspect, which was the most influential variable identified in the DISTLM model.

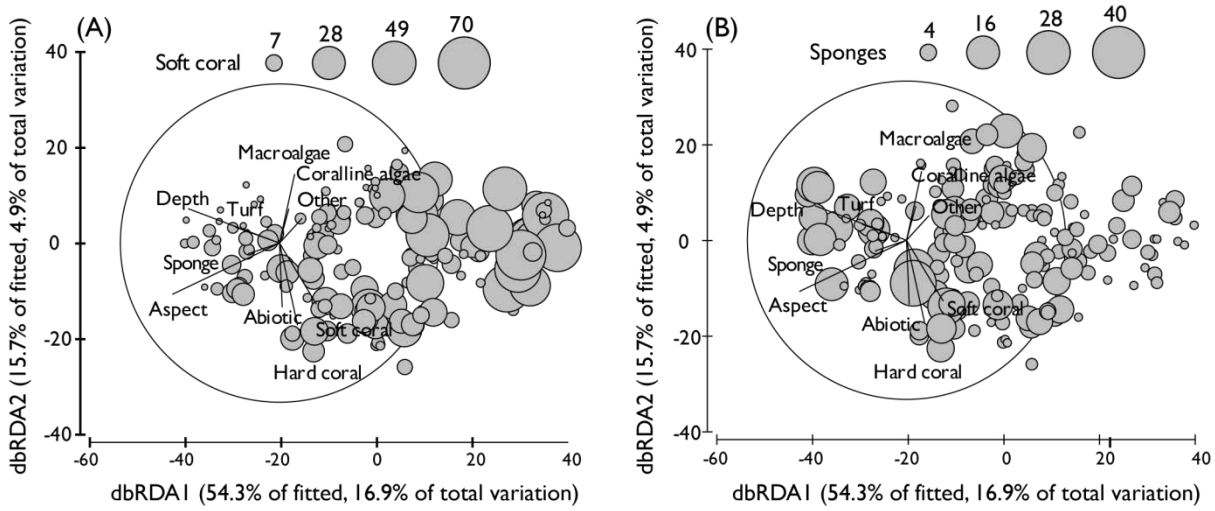

Figure 4.10. dbRDA ordination for the same fitted model as Figure 4.9 but with samples coded for the contributions of the benthic habitats soft coral (A) and sponges (B). Increasing circle size indicates a greater contribution of the respective habitat type. Ordination (A) shows the increase in cover of soft coral from left to right along RDA1 whereas cover of sponges in (B) increases from right to left along RDA1.

4.3.4 Faunal comparisons with other reefs in the region

Comparable UVC data derived from fish surveys at outer slope sites at the Rowley Shoals (Mermaid, Clerke and Imperiuse Reefs) were used to determine whether either of the two reefs potentially exposed to oil (Ashmore and Cartier) displayed any obvious irregularities in terms of general composition of fish communities.

Damselfishes (Pomacentridae) dominated the fish fauna at all reefs, particularly the three most northern reefs where they comprised between *ca* 80 to 90% of the fauna (Figure 4.11 A). In contrast, pomacentrids only contributed between *ca* 60 to 70% of the fauna at each of the three Rowley Shoals reefs in the south. A further notable contrast was that, while the genus *Chrysiptera* contributed 5 to 10% at Ashmore and Seringapatam it contributed <1% at Cartier (Figure 4.11 B).

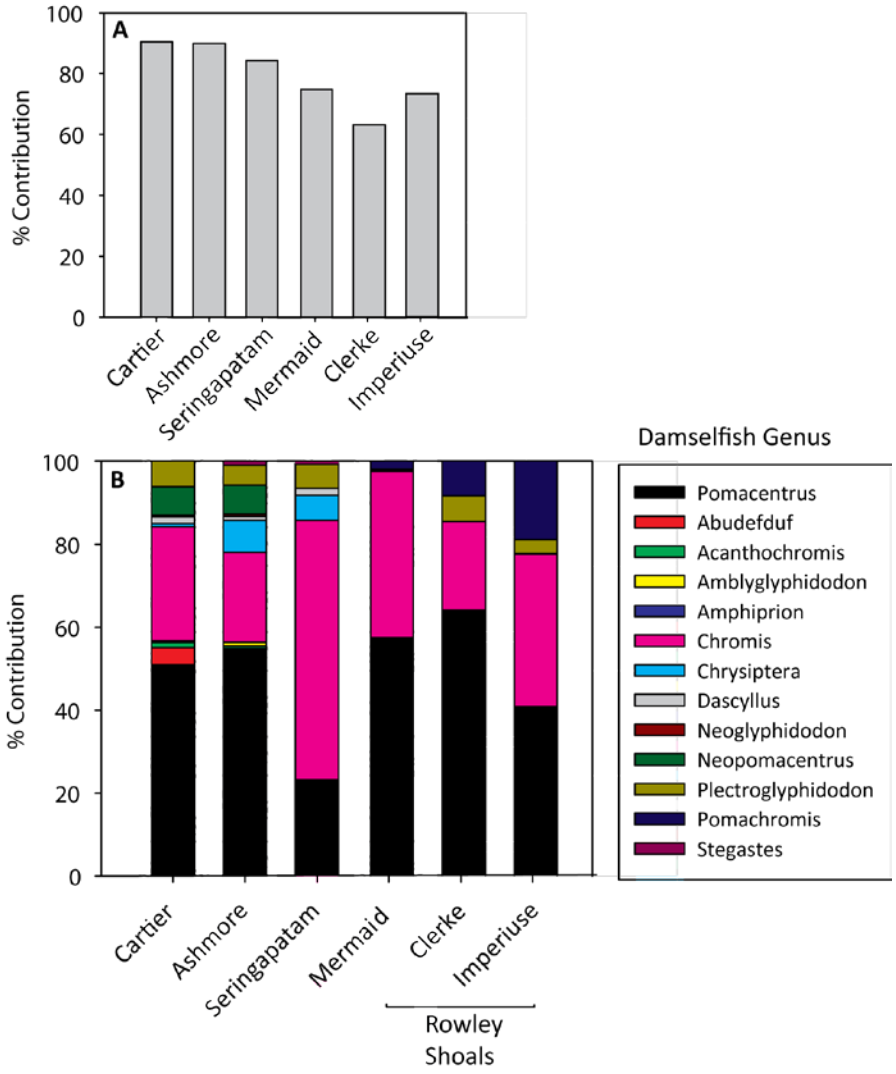

Figure 4.11. Comparison of the contribution of damselfishes to the (A) total numbers of fishes recorded at slope (6 m) locations at six reef systems. This family contributes at least 60% to the numbers of fish at each reef and as high as 90% at the two most northern reefs. (B) Breakdown of the percentage contributions of the various damselfish genera to the total number of pomacentrids. Data in this figure and figures 12 and 13 are based on comparative UVC surveys in 6 m water depth between December 2010 and March 2011.

Figure 4.12 shows the comparison of the contributions of the fish faunas when individual species have been classified according to four of the seven main functional groups. The most noteworthy result is that the relative contribution of secondary consumers is much greater at each of the three reefs of the Rowley Shoals, where fishing is restricted, than at the three most northern reefs, where there is a current and past history of recreational, and particularly traditional fishing (Meekan & Cappo 2004).

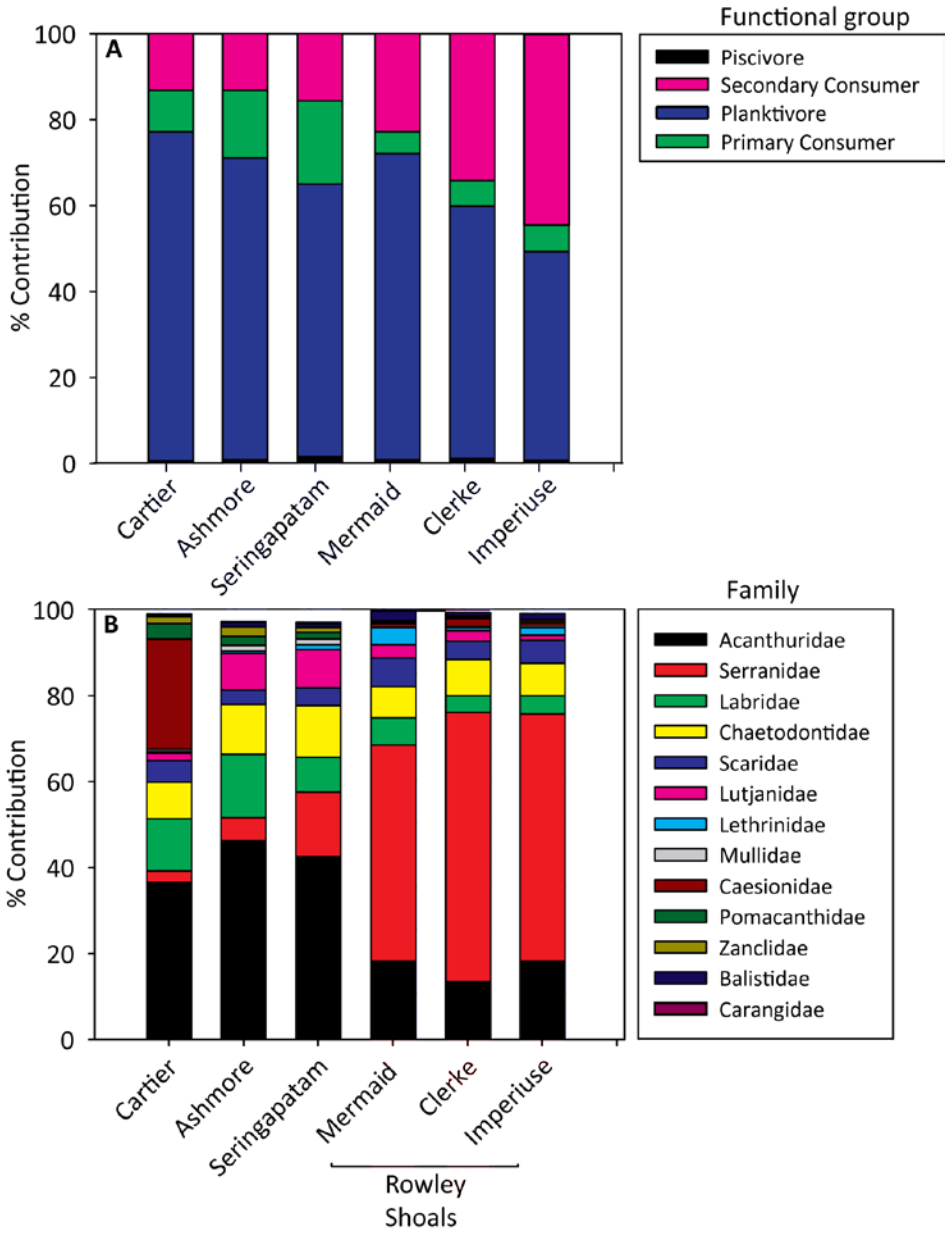

Figure 4.12. Contributions of the four main functional groups of fishes (A) and families of fishes, other than damselfishes (B), to the fish faunas at six offshore reefs in north-western Australia. The contribution of secondary consumers sequentially increases at the non-fished reefs of the Rowley Shoals, which is reflected in the greater contribution of the Serranidae (groupers) at these reefs.

In terms of the non-pomacentrid contributions to the overall fauna, the contribution of surgeonfish (Acanthuridae) was far greater at the three northern-most reefs, whereas the contribution of the highly targeted groupers (Serranidae) was small in comparison with its large contribution at the Rowley Shoals, where this group is afforded protection from any form of fishing. The greater contribution of caesionids at Cartier Reef reflects the schooling planktivore *Caesio teres* that was occasionally recorded in very high numbers. Wrasses (Labridae) made a greater contribution to the fauna at Cartier, Ashmore and Seringapatam Reefs in the north than at the Rowley Shoals in the south. Furthermore, the surgeonfish (Acanthuridae) made a conspicuously high contribution to the fauna at the three most northern reefs, compared to the Rowley Shoals.

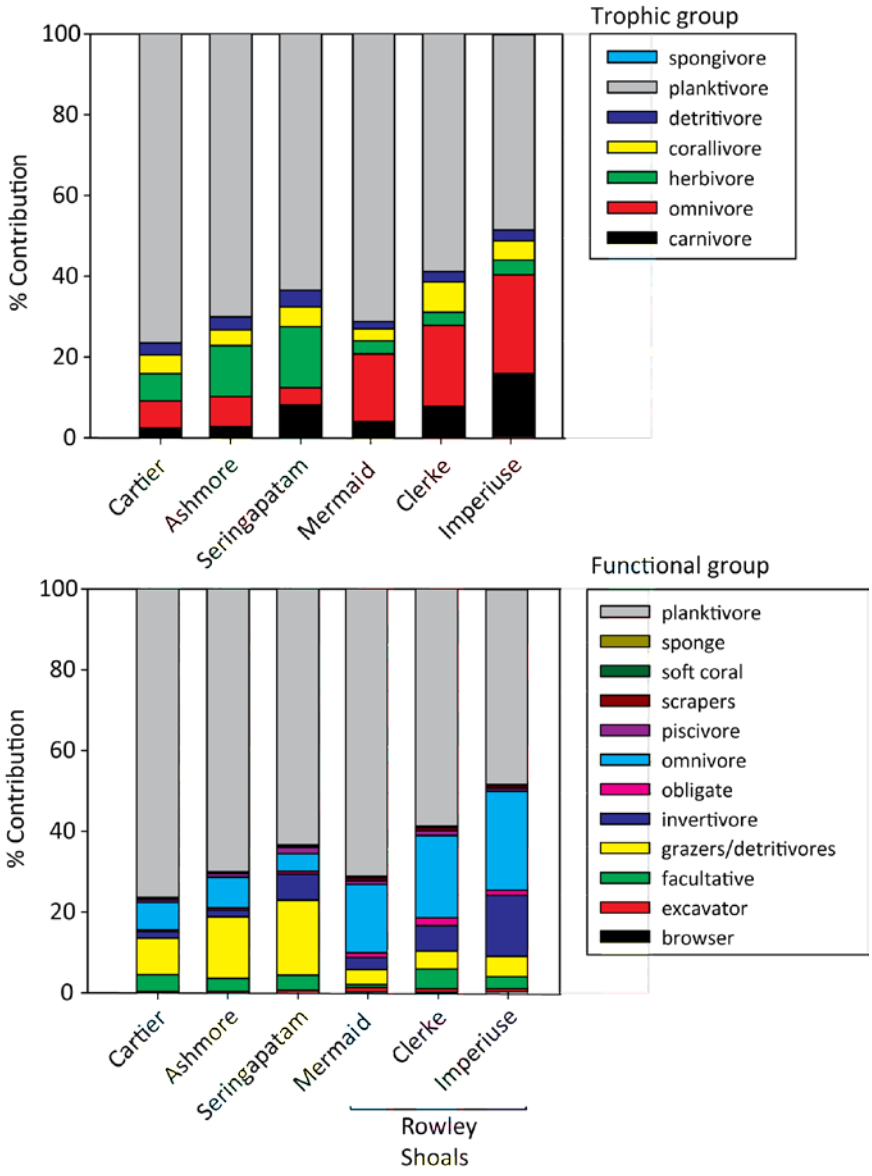

Figure 4.13. Contributions of the seven trophic groups of fishes (A) and of species categorised at functional levels (B), to the fish faunas at six offshore reefs in north-western Australia. Herbivores make greater contributions to the fauna at the four northern than southern reefs, whereas the reverse was the case for omnivorous species.

4.3.5 Size structure of fish communities

Length-frequency analyses using the MIX routine identified multiple modes in the damselfish data (Figure 4.14). The principle mode at Ashmore and Cartier Reefs in both 6 m and 3 m depths was *ca* 40 mm, whereas at Seringapatam it was slightly greater at *ca* 50 mm. Thus, there was no conclusive evidence that the smaller size classes were disproportionately represented at Ashmore and Cartier compared to Seringapatam. Analyses of two abundant damselfishes also found no evidence of truncation in the length-frequency distributions (Figure 4.15). Modal lengths were generally similar among reefs for surgeonfish and damselfish at Ashmore and Cartier Reefs, however, the larger secondary mode/cohort at *ca* 350 mm for parrotfishes (Scaridae) at both depths at Seringapatam was missing at both Ashmore and Cartier Reefs (Figure 4.16).

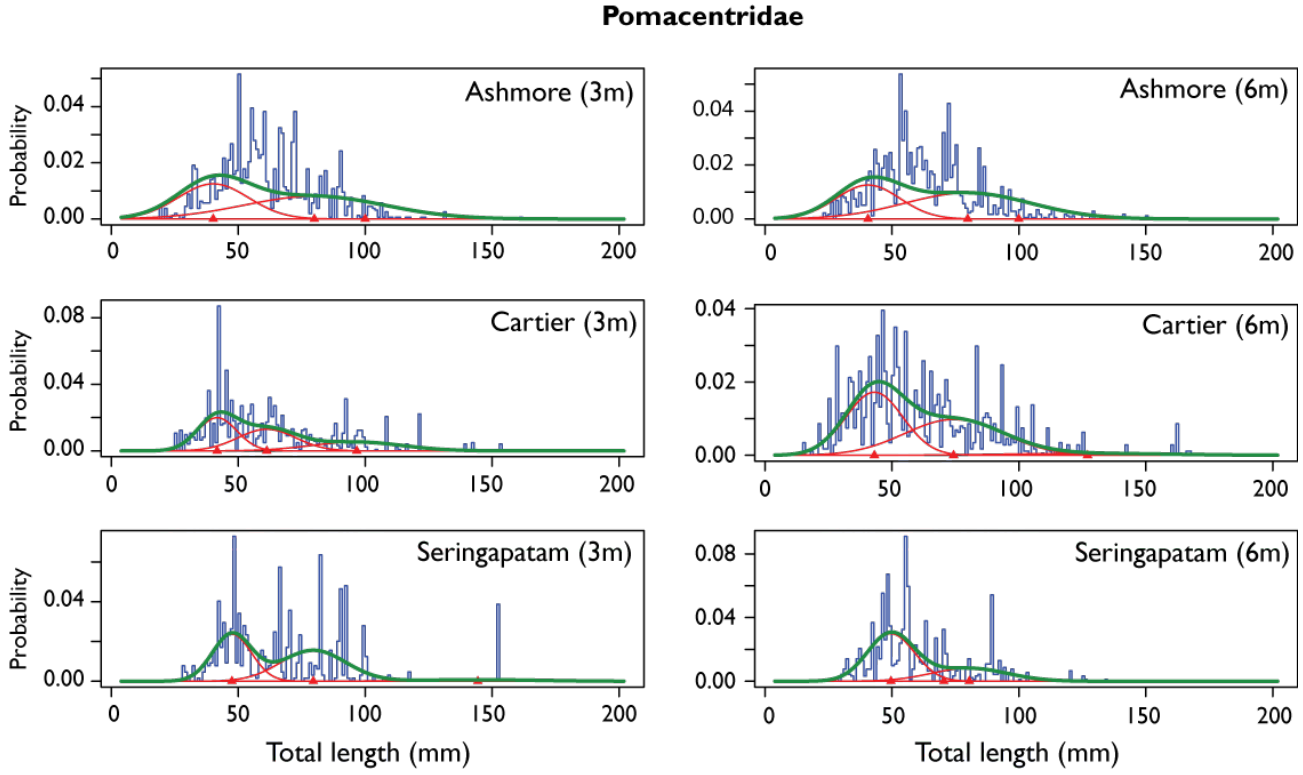

Figure 4.14. Fish length-frequency distributions (bars), principal modes estimates (red lines) and total fit (green line) for damselfishes in 3 m and 6 m sites at Ashmore, Cartier and Seringapatam Reefs in 2011. Red triangles show the mean lengths of each component group.

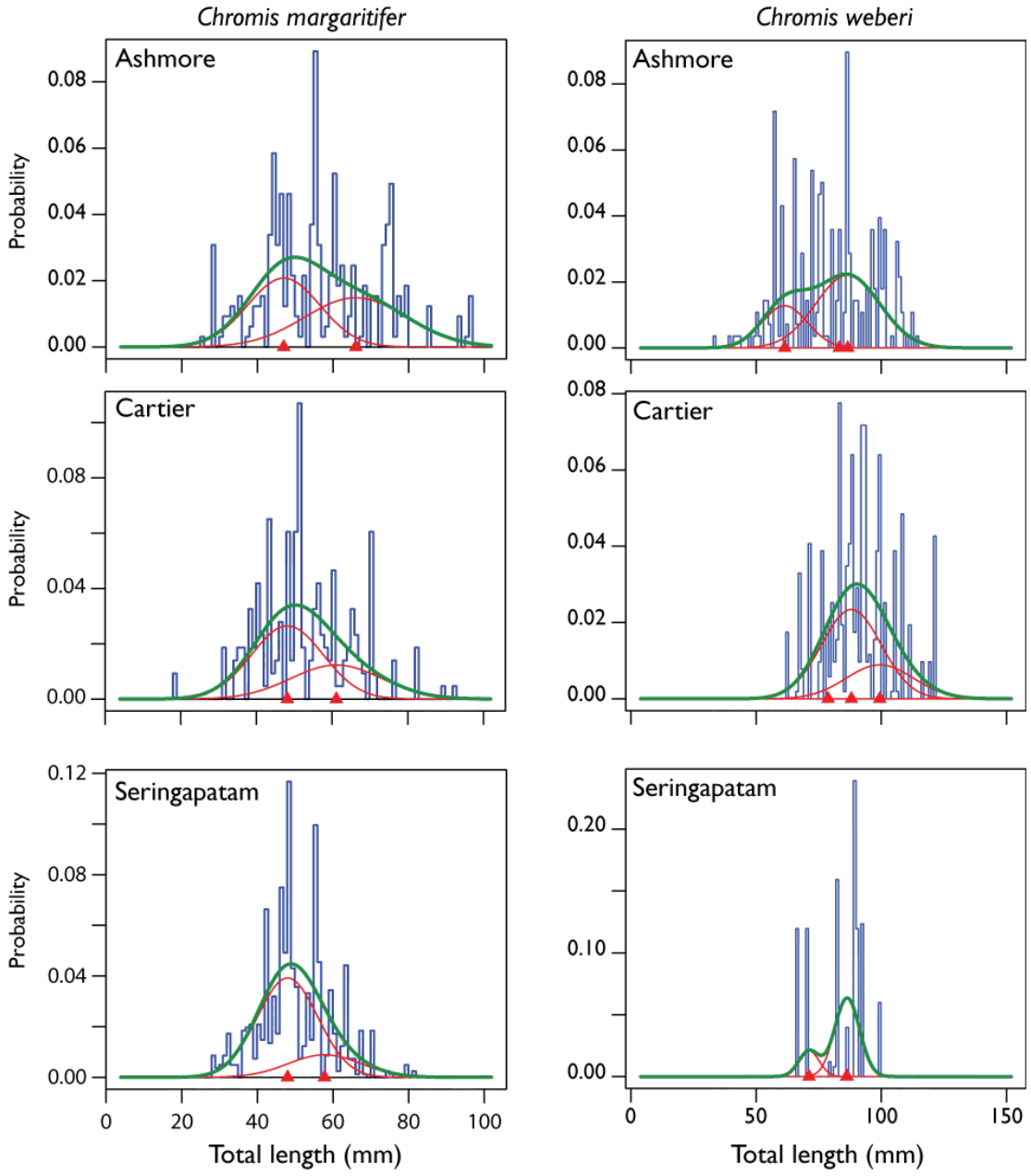

Figure 4.15. Fish length-frequency distributions (bars), principal modes estimates (red lines) and total fit (green line) for *Chromis margaritifer* and *Chromis weberi* at Ashmore, Cartier and Seringapatam Reefs in 2011. Red triangles show the mean lengths of each component group.

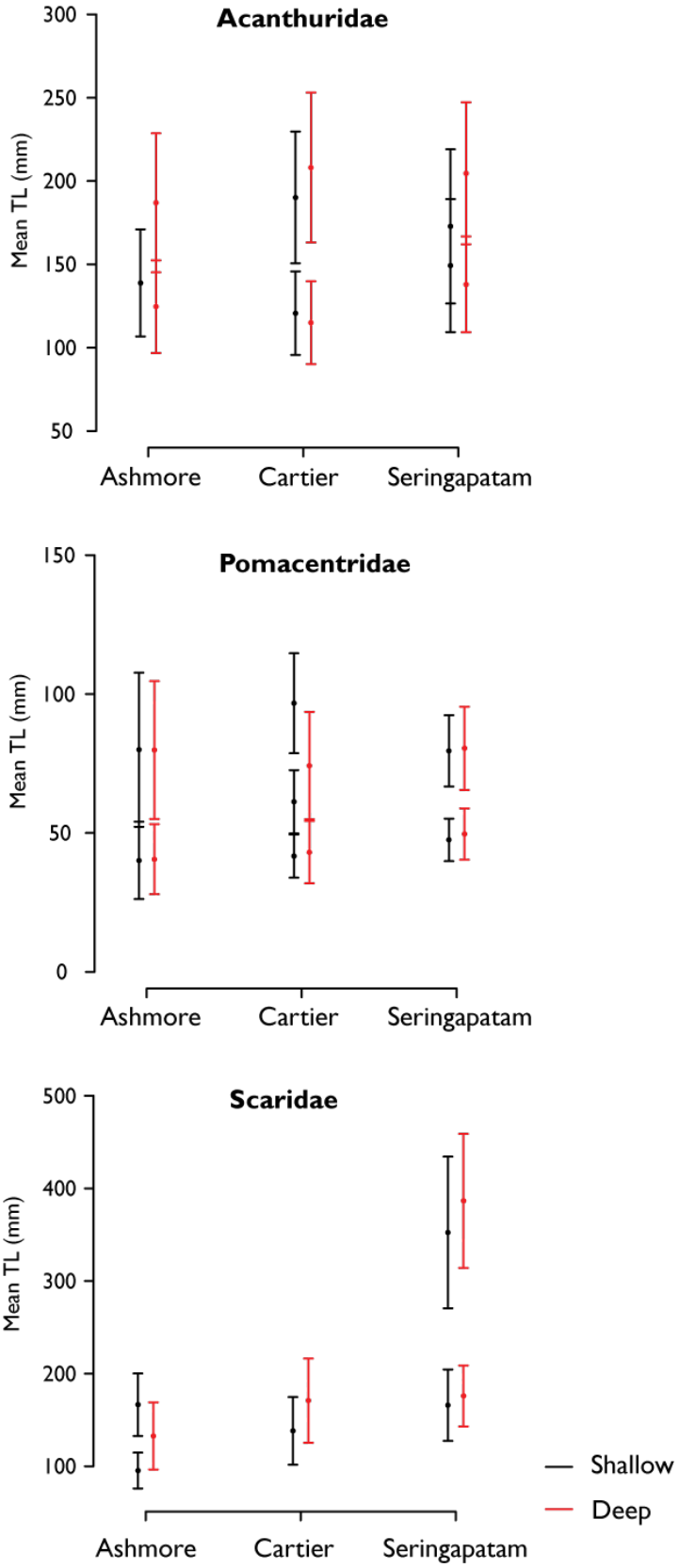

Figure 4.16. Mean (± 1 SD) modal lengths of three main families of fishes determined from a mixed cohort procedure. A second mode is illustrated by a second mean length for a particular depth at a reef. While the parrotfishes (Scaridae) had modes < 200 mm at Ashmore and Cartier, longer secondary modes (> 300 mm) were identified in both depths at Seringapatam.

4.3.6 Comparison of reef fish faunas recorded by UVC and stereo DOV techniques

Four-way ANOVA demonstrated that both the species richness and density of fishes were influenced significantly by sampling method (UVC *vs* DOV), reef, water depth and site within each reef system, and there were no significant interactions (Table 4.9). The mean square values suggest that both species richness and density were most strongly related to sampling method, with water depth being the next most important factor for both of these biotic variables, followed by reef in the case of richness and site for density.

The total numbers of species and fishes recorded and the mean species richness and density of fishes (Figure 4.17 A-D) were greater for UVC than DOV both within and among reefs. Separate ANOVA tests confirmed that species richness and density were significantly greater for UVC overall ($P < 0.01$) and also at Ashmore and Seringapatam Reefs in the case of richness ($P < 0.01$) and at Ashmore Reef in the case of density ($P < 0.05$) (Figure 4.17 B, D). The greater species richness demonstrated by UVC is emphasised by the fact that, of the 258 species recorded using this method, 108 (41.8%) were not recorded by DOV (Appendix 4.1). Furthermore, regression plots of the relationship between the two methods for species richness and densities of fishes illustrated that, although there is a positive linear relationship between the two methods, the values for UVC were greater than those for DOV and often markedly so (Figure 4.18 A, B).

Table 4.9. Results of four-factor ANOVA for species richness (a) and density of fishes (b). Mean squares (MS), *F* ratios and significance level are provided. df = degrees of freedom.

Source	*df*	(a) Species richness			(b) Density		
		MS	*F*	P	MS	*F*	P
Method (M)	1	88.9	73.4	**<0.001**	1174	17.1	**<0.001**
Reef (R)	2	7.7	6.4	**<0.05**	298	4.3	**<0.05**
Depth (D)	1	9.7	8.0	**<0.05**	456	6.6	**<0.05**
Site (M x R x D)	67	1.2	6.4	**<0.001**	69	5.5	**<0.001**
M x R	2	0.3	0.2	0.79	33	0.5	0.614
M x D	1	0.6	0.5	0.49	62	0.9	0.344
R x D	2	0.7	0.6	0.54	8	0.1	0.891
M x R x D	2	1.2	1.0	0.36	5	0.06	0.935
Residual	395	0.2			12		
Total	473						

Significant values in bold

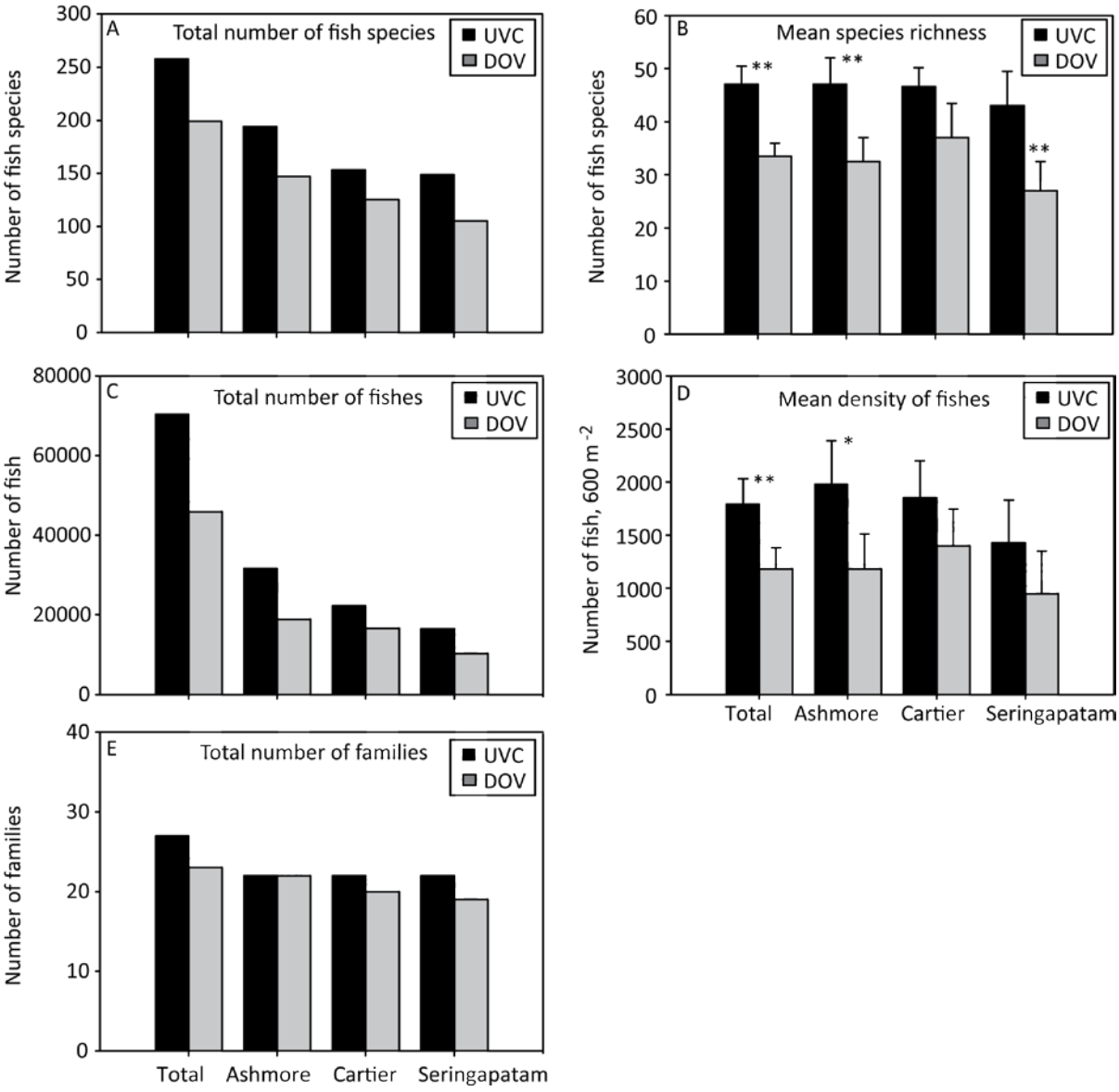

Figure 4.17. Comparison of the characteristics of the fish faunas sampled using underwater visual census (UVC) and diver operated video (DOV) at three offshore reefs in north-western Australia. At each reef the UVC method consistently recorded a higher total number of fish species (A) and fishes (C) and also a generally higher total number of families (E) at two of the three reefs. Mean species richness and density of fishes using UVC were consistently greater than DOV and in many cases this difference was significant (B, D). * = $P < 0.05$; ** = $P < 0.01$.

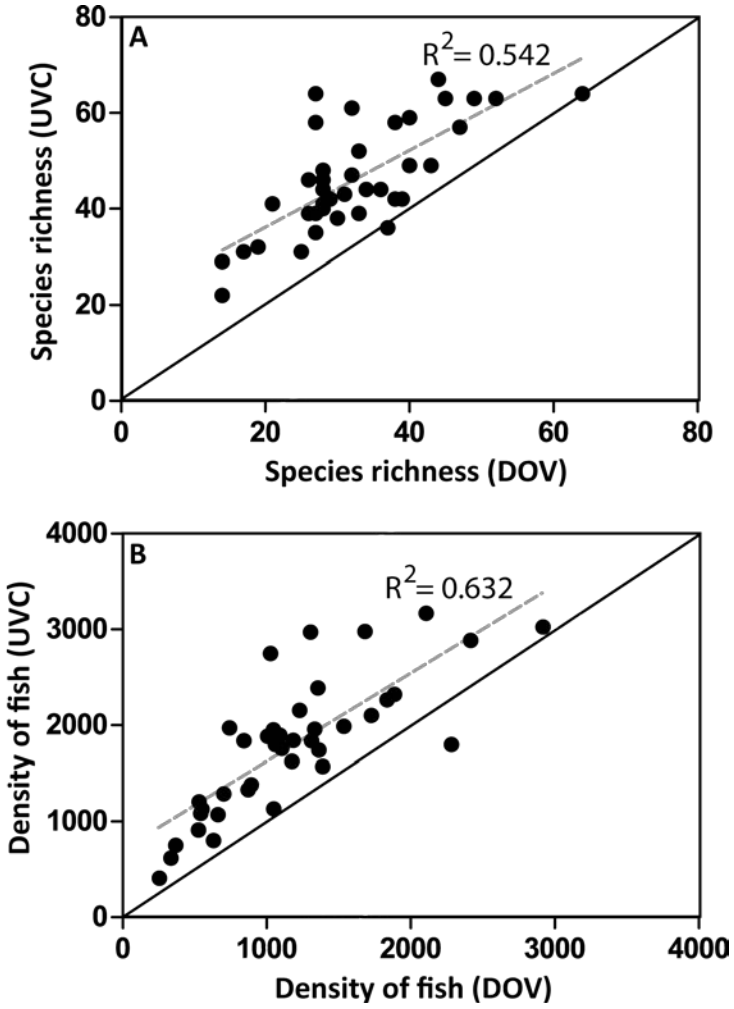

Figure 4.18. Relationship between the number of species (A) and density (B) recorded using underwater visual census (UVC) and diver operated video (DOV) methods for surveying fish communities at Ashmore, Cartier and Seringapatam Reefs in 2011. Both species richness and densities recorded using the UVC method tended to be greater than those recorded by DOV.

PERMANOVA demonstrated that the species composition of reef fish assemblages was significantly related to method (UVC *vs* DOV), reef, depth and site within reefs (all $P < 0.001$), and there were no significant interactions between any of these main effects (Table 4.10 a). Furthermore, these main effects were still significant when the multivariate data were analysed at progressively lower levels of taxonomic resolution including genus and family (Table 4.10 b, c). In terms of species level data, the mean square values emphasise that composition was most strongly related to the effect of reef, although values for method and depth were similar. When the mean densities of the various fishes recorded at each site at each reef were analysed using non-metric multidimensional scaling (nMDS) ordination, the samples showed a clear tendency to form groups on the basis of reef system (Figure 4.19 A). Differences between methods were most clearly illustrated when mean data were ordinated separately for each reef, with samples for UVC and DOV grouping separately, particularly at Ashmore and Seringapatam Reefs (Figure 4.19 B-D).

Table 4.10. Results of four-factor PERMANOVA examining the effects of sampling method (UVC *vs* DOV), reef (Ashmore, Cartier and Seringapatam), depth (deep and shallow) and site within a reef (nested) on reef fish composition at the species (a), genus (b) and family (c) levels. Analyses were based on the Bray-Curtis dissimilarity measure for $\log_{e^{10}}$ transformed density data. Mean squares (MS), pseudo-*F* ratios and significance level are provided. df = degrees of freedom.

Source	*df*	(a) Species			(b) Genus			(c) Family		
		MS	*F*	P	MS	*F*	P	MS	*F*	P
Method (M)	1	54877	6.9	**<0.001**	37535	10.3	**<0.001**	12137	8.9	**<0.001**
Reef (R)	2	60265	7.7	**<0.001**	24681	6.7	**<0.001**	3111	2.3	**0.015**
Depth (D)	1	55481	7.1	**<0.001**	26946	7.4	**<0.001**	12680	9.4	**<0.001**
Site (M x R x D)	67	7852	6.3	**<0.001**	3653	4.8	**<0.001**	1350	3.9	**<0.001**
M x R	2	6386	0.8	0.69	2400	0.7	0.875	765	0.5	0.850
M x D	1	11304	1.4	0.14	4274	1.2	0.292	982	0.7	0.595
R x D	2	8684	1.1	0.31	4783	1.3	0.160	2535	1.9	0.053
M x R x D	2	4151	0.5	0.97	1170	0.3	0.999	325	0.2	0.995
Residual	395	1247			753					
Total	473									

Values in bold are significant

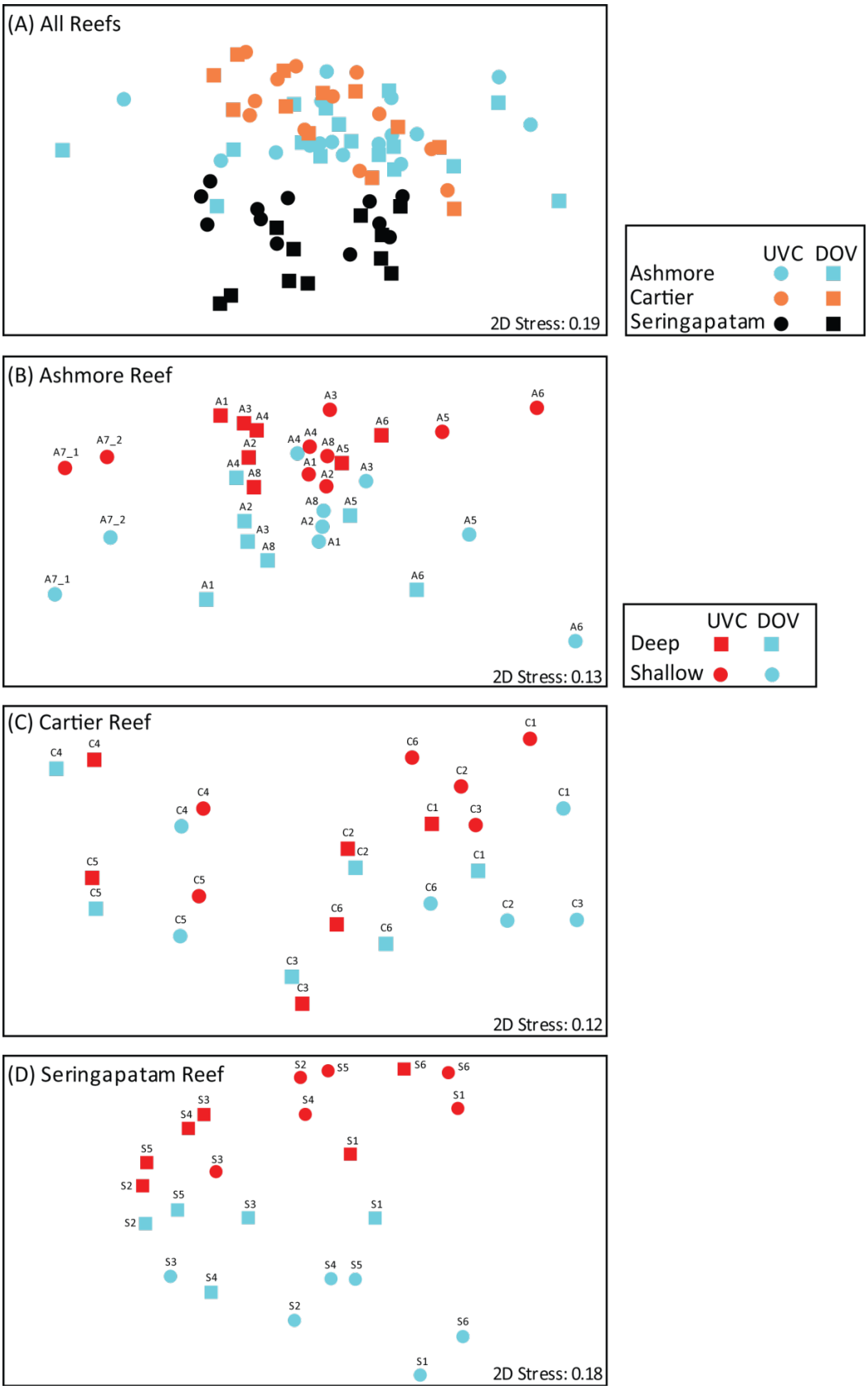

Figure 4.19. Non-metric multidimensional scaling (nMDS) ordination plots showing the separation of the samples according to method (UVC *vs* DOV) and reef system (A) and according to method and depth at Ashmore (B), Cartier (C) and Seringapatam Reefs (D).

SIMPER analyses showed that the differences in species composition between the two methods at each reef were largely attributable to higher numbers of certain damselfishes, butterflyfishes and wrasses recorded by UVC in contrast to higher numbers of unidentified species of damselfishes, wrasses and triggerfishes by DOV. Composition of UVC samples were distinguished by relatively high densities of the damselfishes *Chrysiptera rex*, *Chromis margaritifer*, *Pomacentrus bankanensis*, *Pomacentrus philippinus* and *Plectroglyphididon lacrymatus*, the wrasses *Thalassoma jansenni* and *Halichoeres margaritaceus* and the butterflyfish *Chaetodon citrenellus*. In contrast, DOV samples were distinguished by higher densities of unidentified damselfishes (*Pomacentrus* spp.), wrasses (*Halichoeres* spp.) and triggerfishes (*Balistid* spp.).

4.3.7 Parasitism of fishes by cymothoid isopods

During fish surveys a high number of damselfish were observed with a single large cymothoid isopod attached to their head region at Ashmore and Cartier Reefs, (Figure 4.20). These ectoparasitic isopods occurred on fifteen species of damselfish at Ashmore and Cartier Reefs, but were absent from all other reef fishes and did not occur on fishes at Seringapatam Reef (Table 4.11). While this observation has previously been noted at Ashmore and Cartier Reefs (Richards et al. 2009), and therefore cannot be attributed to the uncontrolled release of hydrocarbons, the underlying causal factors may relate to a level of disturbance within the environment at these two reefs.

Cymothoid isopods are ectoparasites of marine fishes throughout the worlds tropical oceans (Brusca 1981). They are protandrous hermaphrodites (Bullar 1876) that do not leave their hosts once becoming females (Bunkley-Williams & Williams 1998), and have modified mouthparts that enable them to attach to the outer skin and scale layer of fishes to feed on their blood, often causing skin tissue damage (Brusca 1981). The isopods observed at these reefs are likely to belong to the *Anilocra* spp group, which are among the largest sized cymothoid ispods, commonly attaching to the head region or anterior third of a fishes body, and always occurring as single infestations (Fogelman & Grutter 2008).

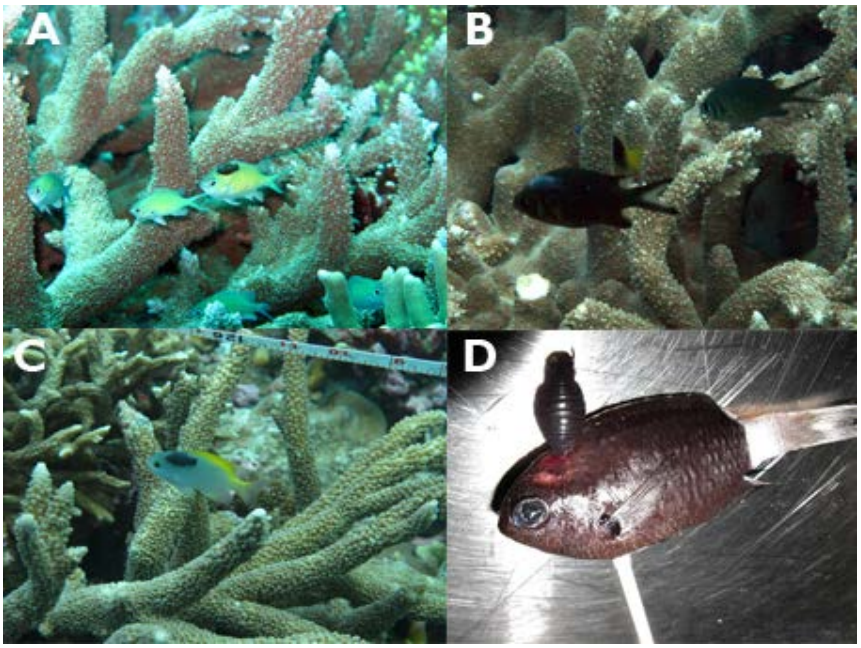

Figure 4.20. Examples of the parasitic isopods attached to various damselfish species at Ashmore and Cartier Reefs. (A) *Chromis viridis*, (B) *Chromis weberi*, (C) *Pomacentrus lepidogenys* and (D) *Chromis margaritifer*, with tissue damage to the head region.

Table 4.11. List of the fifteen damselfish species infested with cymothoid isopods at Ashmore and Cartier Reefs in 2011. No isopods were observed at Seringapatam Reef.

Species	Ashmore	Cartier
Chromis atripes	✓	×
Chromis lepidolepis	×	✓
Chromis margaritifer	✓	✓
Chromis ternatensis	✓	×
Chromis viridis	✓	✓
Chromis weberi	✓	✓
Chromis xanthura	×	✓
Dascyllus reticulatus	✓	×
Plectroglyphidodon lacrymatus	✓	✓
Pomacentrus bankanensis	✓	✓
Pomacentrus coelestis	✓	×
Pomacentrus lepidogenys	✓	✓
Pomacentrus philippinus	×	✓
Pomacentrus vaiuli	✓	✓
Stegastes fasciolatus	✓	✓

4.4 Conclusions

Our study did not include surveys of fish communities prior to the Montara uncontrolled release and for this reason, we cannot clearly attribute any patterns seen in the assemblages of fishes on reef to impacts of this event. While keeping this important caveat in mind, we did find some differences in composition of fish assemblages among reefs that, although they could also be explained by factors such as prior histories of disturbance (e.g. coral bleaching and cyclonic damage) might also be indicative of reefs that have been exposed to hydrocarbons from an uncontrolled release. For example, the fish species whose differences in abundance particularly influenced differences in assemblage composition were damselfishes with life-cycle characteristics (benthic nests of eggs) that might make them more susceptible to the negative effects of HCs present within the reef substratum or sediments (Norcross et al. 1996). Trace levels of HCs were detected at the reefs (Chapter 5), but when sampled months after cessation of the Montara uncontrolled release, these were not at levels expected to have negative effects on fishes.

Multivariate analyses of species composition data showed that the structure of fish assemblages at Seringapatam Reef, a reef less likely to have been exposed to the Montara uncontrolled release, was significantly different from those of both Ashmore and Cartier Reefs. The sediments at both Ashmore and Cartier Reefs were shown to generally have higher HC levels than Seringapatam (Chapter 5). This result was mainly attributable to lower densities of the damselfishes *Chromis margaritifer*, *Chrysiptera rex* and *Plectroglyphidodon dickii* and higher densities of *Pomacentrus lepidogenys* and *Pomacentrus coelestis* at Ashmore and Cartier than Seringapatam Reefs. It is noteworthy that in a broad-scale temporal study (1000s km, decades) on the impacts of disturbance (cyclones and coral bleaching) on reef fish communities on the Great Barrier Reef, the latter damselfish, *P. coelestis*, was the only species demonstrating an increase in abundance following the loss of live coral and remained one of the most abundant species on disturbed reefs (Halford et al. 2004). In addition,

juveniles of this species are known to recruit preferentially to degraded habitats (Syms & Jones 2000). Whether the higher densities of *P. coelestis* at Ashmore, and particularly at Cartier Reefs, had been created by disturbance events, such as the loss of live coral and increases in availability of preferred recruitment habitat (dead coral rubble), or whether this pattern simply reflects other recruitment processes such as enhanced survivorship of planktonic larvae, cannot be determined without data on the benthic habitats prior to the Montara uncontrolled release. Furthermore, conversion of live coral to the preferred recruitment habitat of dead coral rubble can happen through a number of natural processes such as coral bleaching, crown-of-thorns (*Acanthaster planci*) outbreaks and coral disease (Ninio et al. 2000, Miller et al. 2009, Osborne et al. 2011). Reefs in the region are prone to regular cyclonic storm impacts. Consequently, these processes, either separately or in synergy with, the effects of the Montara uncontrolled release, could also lead to the observed patterns in fish communities.

Low densities of the damselfish *Plectroglyphidodon dickii* were found at Ashmore and Cartier Reefs. This species dwells within live *Pocillopora eydouxi* coral colonies, which are particularly susceptible to coral bleaching. There was a minor coral bleaching event in the region in early 2010 (Chapter 2) and although there was no significant decline in total cover of pocilloporid corals at Ashmore and Cartier Reefs between 2010 and 2011 (Section 2.3), cover did decline at four of the seven sites at Ashmore Reef. Thus, bleaching may explain some of the differences in species composition we found among the three reefs.

Additional evidence that natural disturbances have affected the composition of fish communities at our study reefs is provided by the comparison of fish community structure of Ashmore, Cartier and Seringapatam Reefs with those of the Rowley Shoals. Our study reefs had a higher proportion of herbivorous fishes, notably acanthurids, than the Rowley Shoals. Herbivores such as these typically increase in response to the loss of live coral and its replacement by turfing algae on which they graze (Mumby et al. 2006, Mumby 2009, Wilson et al. 2009). The higher abundances of these functional groups at the Rowley Shoals probably reflect an earlier history of disturbance (coral bleaching, fishing, cyclones etc).

We found no obvious patterns in species richness, biomass, density and size-structure of fish assemblages that were consistent with effects following the Montara uncontrolled release and subsequent clean-up efforts. This could mean that the eggs/larvae and older life stages of fishes at these reefs did not come into contact with oil products during the period of the Montara uncontrolled release or that reef fishes and/or their eggs/larvae were resilient to exposure. Alternatively, the timing of spawning and/or time that fish larvae were in the water column may not have coincided with the period of oil exposure.

There appeared to be no impacts of the Montara uncontrolled release on the recruitment of the reef fishes, since we found no evidence of missing or truncated size classes in size-frequency distributions of fishes at Ashmore, Cartier and Seringapatam Reefs. It is possible that those fish that survived the exposure to HCs (Chapter 5) or settled to the reef in the immediate aftermath of the uncontrolled release grew at accelerated rates due to the removal of earlier settlers that under normal circumstances would have competed with them for benthic resources. This would have reduced any likelihood of finding effects of the uncontrolled release in size-frequency distributions. In order to examine this possibility, analysis of the age structure of fish communities is now required. This would show if any age classes that coincided with the timing of the release were missing from the population. Additionally, such analyses would allow growth patterns to be reconstructed, so that any delayed effects of exposure could be documented. In other systems, effects of uncontrolled releases on growth, survival and reproduction have been demonstrated many years after exposure to hydrocarbons (Heintz et al. 2000). These effects can be exacerbated by hydrocarbons remaining present in sediments, which could be harmful for species that lay benthic eggs, as is the case for many reef fishes. Other studies have implicated these long-term impacts of spills in the creation of

instabilities in marine ecosystems and the delayed collapse of fisheries stocks (Pearson et al. 1999, Carls et al. 2002), albiet at levels of hydrocarbons much greater than those detected in the present study (Chapter 5).

As mentioned earlier, all of our conclusions must be considered in light of the "snapshot" nature of our study. We lacked pre-release data on which to base any assessment of the effects of the Montara uncontrolled release. Ideally, such data should be collected over a time frame and at a spatial scale sufficient to encompass the cycles of disturbance and recovery that most reefs undergo at inter-annual scales. For coral reefs, this would require a baseline of at least a decade. Given that the study reefs are isolated from other coral environments and appear to have limited connectivity (AIMS unpublished data), it would be reasonable to predict that their recovery from large disturbances would be slower than on reefs within more connected, archipelagic systems such as the Great Barrier Reef. However, the limited data available suggests that this is not the case, since the rate of recovery of corals from bleaching at Ashmore Reef described by Ceccarelli et al. (2011) lie within the typical rates of change recorded for other reefs of the Great Barrier Reef (AIMS unpublished data).

Our study highlights the value of having a long-term monitoring programme in place in areas at high risk of release of hydrocarbon products into the ocean. Such monitoring programs provide data that can be used to derive causal links for observed patterns and, most importantly, give researchers and managers the ability to determine whether observed changes are part of the natural variability in dynamic marine ecosystems, or reflect a response to human activities.

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Appendix 4.1. List of fish species and their families recorded using both UVC and DOV at three reefs systems in North-western Australia in 2011.

		Species presence		
FAMILY	Species	UVC	DOV	Abundance
Acanthuridae	*Acanthurus auranticavus*	9	-	9
	Acanthurus bariene	1	-	1
	Acanthurus blochii	26	11	37
	Acanthurus dussumieri	1	-	1
	Acanthurus leucocheilus	8	-	8
	Acanthurus lineatus	283	112	395
	Acanthurus maculiceps	10	-	10
	Acanthurus mata	20	-	20
	Acanthurus nigricans	389	267	656
	Acanthurus nigricauda	17	-	17
	Acanthurus nigrofuscus	331	2	333
	Acanthurus olivaceus	56	13	69
	Acanthurus pyroferus	43	29	72
	Acanthurus spp	-	47	47
	Acanthurus triostegus	1	-	1
	Ctenochaetus binotatus	3	-	3
	Ctenochaetus sp1	-	6	6
	Ctenochaetus spp	2228	1713	3941
	Naso brachycentron	13	3	16
	Naso brevirostris	8	-	8
	Naso caesius	11	6	17
	Naso hexacanthus	-	6	6
	Naso lituratus	29	15	44
	Naso spp	-	1	1
	Naso thorpei	7	6	13
	Naso vlamingii	13	7	20
	Zebrasoma scopas	80	41	121
	Zebrasoma veliferum	12	3	15
Balistidae	*Balistapus undulatus*	2	-	2
	Balistid spp	-	1	1
	Balistoides conspicillum	1	1	2
	Melichthys niger	4	-	4
	Melichthys sp	-	1	1
	Melichthys vidua	10	2	12
	Odonus niger	1	-	1
	Odonus spp	-	1	1
	Rhinecanthus aculeatus	2	-	2
	Rhinecanthus cinereus	1	-	1
	Rhinecanthus rectangulus	2	3	5
	Rhinecanthus verrucosus	6	-	6
	Sufflamen bursa	4	2	6
	Sufflamen chrysopterum	-	21	21
	Sufflamen chrysopterus	78	-	78
	Sufflamen spp	-	9	9
Caesionidae	*Caesio caerulaurea*	132	-	132
	Caesio spp	-	5	5
	Caesio teres	80	37	117
	Pterocaesio pisang	78	-	78
	Pterocaesio sp1	-	25	25
	Pterocaesio spp	-	28	28
	Pterocaesio trilineata	1	-	1
Carangidae	*Carangoides ferdau*	15	11	26

	Carangoides orthogrammus	1	61	62
	Caranx melampygus	12	7	19
Carcharhinidae	*Triaenodon obesus*	2	1	3
Chaetodontidae	*Chaetodon adiergastos*	22	7	29
	Chaetodon auriga	6	6	12
	Chaetodon baronessa	42	19	61
	Chaetodon bennetti	1	-	1
	Chaetodon citrinellus	123	61	184
	Chaetodon decussatus	-	1	1
	Chaetodon ephippium	13	8	21
	Chaetodon flavirostris	-	1	1
	Chaetodon kleinii	64	44	108
	Chaetodon lineolatus	2	4	6
	Chaetodon lunula	1	6	7
	Chaetodon lunulatus	102	87	189
	Chaetodon melannotus	19	25	44
	Chaetodon meyeri	29	11	40
	Chaetodon ocellicaudus	14	-	14
	Chaetodon ornatissimus	22	11	33
	Chaetodon plebeius	1	-	1
	Chaetodon punctatofasciatus	25	6	31
	Chaetodon rafflesii	5	4	9
	Chaetodon semeion	1	1	2
	Chaetodon sp1	-	2	2
	Chaetodon speculum	1	-	1
	Chaetodon spp	-	1	1
	Chaetodon trifascialis	83	39	122
	Chaetodon trifasciatus	30	2	32
	Chaetodon ulietensis	37	21	58
	Chaetodon unimaculatus	4	-	4
	Chaetodon vagabundus	40	28	68
	Forcipiger flavissimus	47	26	73
	Forcipiger longirostris	1	-	1
	Hemitaurichthys polylepis	7	15	22
	Heniochus acuminatus	2	-	2
	Heniochus chrysostomus	16	11	27
	Heniochus monoceros	6	3	9
	Heniochus singularius	2	-	2
	Heniochus varius	10	6	16
Cirrhitidae	*Cirrhitichthys oxycephalus*	1	-	1
	Paracirrhites arcatus	4	-	4
	Paracirrhites forsteri	50	47	97
Diodontidae	*Diodon holocanthus*	1	-	1
Ephippidae	*Platax orbicularis*	2	-	2
Ephippidae	*Platax teira*	1	-	1
Fistulariidae	*Fistularia commersonii*	1	-	1
Haemulidae	*Plectorhinchus chaetodonoides*	5	2	7
	Plectorhinchus goldmanni	3	-	3
	Plectorhinchus lineatus	24	22	46
	Plectorhinchus multivittatus	-	2	2
	Plectorhinchus paulayi	1	-	1
	Plectorhinchus spp	-	1	1
	Plectorhinchus vittatus	5	11	16
Holocentridae	*Myripristis* sp1	-	2	2
	Neoniphon argenteus	-	4	4
	Neoniphon sammara	-	1	1
	Sargocentron spiniferum	-	1	1
Hydrophiidae	*Hydrophis* spp	-	1	1
Kyphosidae	*Kyphosus bigibbus*	6	-	6

Labridae	*Anampses caeruleopunctatus*	1	-	1
	Anampses geographicus	1	-	1
	Anampses meleagrides	1	-	1
	Anampses twistii	2	-	2
	Bodianus axillaris	27	11	38
	Bodianus diana	4	-	4
	Bodianus mesothorax	2	3	5
	Bodianus spp	4	-	4
	Cheilinus chlorourus	7	1	8
	Cheilinus fasciatus	24	5	29
	Cheilinus trilobatus	10	7	17
	Cirrhilabrus exquisitus	25	-	25
	Coris aygula	2	-	2
	Coris gaimard	6	3	9
	Diproctacanthus xanthurus	2	-	2
	Epibulus insidiator	8	1	9
	Gomphosus varius	146	108	254
	Halichoeres hortulanus	58	28	86
	Halichoeres margaritaceus	177	33	210
	Halichoeres marginatus	31	-	31
	Halichoeres melanurus	7	-	7
	Halichoeres spp	-	293	293
	Halichoeres trimaculatus	2	-	2
	Hemigymnus fasciatus	17	10	27
	Hemigymnus melapterus	9	8	17
	Labrichthys unilineatus	8	-	8
	Labrid spp	-	7	7
	Labroides bicolor	16	15	31
	Labroides dimidiatus	49	58	107
	Labroides pectoralis	-	2	2
	Macropharyngodon meleagris	7	-	7
	Novaculichthys taeniourus	5	-	5
	Oxycheilinus digrammus	30	18	48
	Oxycheilinus orientalis	4	-	4
	Oxycheilinus spp	-	6	6
	Oxycheilinus unifasciatus	23	6	29
	Paracheilinus mccoskeri	8	-	8
	Pseudocheilinus hexataenia	5	-	5
	Pseudocheilinus octotaenia	1	-	1
	Pseudodax moluccanus	5	1	6
	Stethojulis bandanensis	8	-	8
	Stethojulis trilineata	1	-	1
	Thalassoma amblycephalum	205	53	258
	Thalassoma hardwicke	19	15	34
	Thalassoma jansenii	118	91	209
	Thalassoma lunare	130	74	204
	Thalassoma lutescens	29	-	29
	Thalassoma quinquevittatum	220	14	234
	Thalassoma spp	-	12	12
Lethrinidae	*Gnathodentex aureolineatus*	4	3	7
	Lethrinus erythropterus	3	-	3
	Lethrinus obsoletus	6	4	10
	Monotaxis grandoculis	30	13	43
Lutjanidae	*Aphareus furca*	1	-	1
	Aprion virescens	3	-	3
	Lutjanus bohar	19	13	32
	Lutjanus decussatus	71	57	128
	Lutjanus gibbus	150	119	269
	Lutjanus kasmira	6	5	11

	Lutjanus monostigma	41	11	52
	Lutjanus quinquelineatus	1	-	1
	Macolor niger	-	2	2
	Macolor spp	41	2	43
	Paracaesio xanthura	5	-	5
Microdesmidae	*Ptereleotris evides*	-	14	14
	Ptereleotris spp	4	-	4
Monacanthidae	*Aluterus schoepfii*	1	-	1
	Aluterus scriptus	-	1	1
	Cantherhines pardalis	14	3	17
	Cantherhines pullus	1	-	1
	Oxymonacanthus longirostris	2	-	2
Mullidae	*Parupeneus barberinus*	6	1	7
	Parupeneus bifasciatus	13	-	13
	Parupeneus crassilabris	2	3	5
	Parupeneus macronema	4	-	4
	Parupeneus multifasciatus	43	16	59
	Parupeneus trifasciatus	-	10	10
Nemipteridae	*Pentapodus* spp	2	-	2
	Scolopsis bilineata	3	6	9
	Scolopsis margaritifer	14	4	18
Pomacanthidae	*Apolemichthys trimaculatus*	6	1	7
	Centropyge bicolor	3	5	8
	Centropyge vroliki	125	60	185
	Chaetodontoplus mesoleucus	2	-	2
	Pomacanthus imperator	6	2	8
	Pomacanthus navarchus	3	-	3
	Pomacanthus sexstriatus	3	2	5
	Pygoplites diacanthus	12	6	18
Pomacentridae	*Abudefduf bengalensis*	25	-	25
	Abudefduf vaigiensis	765	425	1190
	Acanthochromis polyacanthus	260	175	435
	Amblyglyphidodon aureus	10	25	35
	Amblyglyphidodon curacao	60	10	70
	Amblyglyphidodon leucogaster	20	10	30
	Amblyglyphidodon sp1	-	335	335
	Amblyglyphidodon spp	-	105	105
	Amblyglyphidodon ternatensis	460	-	460
	Amphiprion melanopus	15	-	15
	Chromis atripectoralis	135	125	260
	Chromis atripes	20	-	20
	Chromis lepidolepis	285	15	300
	Chromis margaritifer	9650	6885	16535
	Chromis spp	-	135	135
	Chromis ternatensis	750	545	1295
	Chromis viridis	715	450	1165
	Chromis weberi	6340	5460	11800
	Chromis xanthura	195	90	285
	Chrysiptera bleekeri	50	-	50
	Chrysiptera brownriggii	50	-	50
	Chrysiptera hemicyanea	320	40	360
	Chrysiptera leucopoma	5	-	5
	Chrysiptera rex	2805	680	3485
	Chrysiptera sp1	-	5	5
	Chrysiptera spp	-	30	30
	Chrysiptera talboti	255	-	255
	Dascyllus aruanus	50	35	85
	Dascyllus carneus	10	-	10
	Dascyllus reticulatus	410	320	730

	Dascyllus trimaculatus	80	20	100
	Dischistodus perspicillatus	5	-	5
	Hemiglyphidodon plagiometopon	15	5	20
	Neoglyphidodon melas	60	25	85
	Neoglyphidodon nigroris	235	130	365
	Neoglyphidodon oxyodon	40	-	40
	Neoglyphidodon spp	-	10	10
	Neopomacentrus azysron	3070	2160	5230
	Neopomacentrus spp	5	-	5
	Neopomacentrus violascens	45	-	45
	Plectroglyphidodon dickii	1050	405	1455
	Plectroglyphidodon johnstonianus	1125	425	1550
	Plectroglyphidodon lacrymatus	1175	170	1345
	Plectroglyphidodon sp1	-	5	5
	Plectroglyphidodon spp	-	5	5
	Pomacentrid spp	-	5	5
	Pomacentrus adelus	370	10	380
	Pomacentrus alexanderae	5	-	5
	Pomacentrus amboinensis	140	5	145
	Pomacentrus bankanensis	2155	565	2720
	Pomacentrus coelestis	9600	7490	17090
	Pomacentrus lepidogenys	12230	9425	21655
	Pomacentrus moluccensis	10	10	20
	Pomacentrus pavo	40	-	40
	Pomacentrus philippinus	3520	2315	5835
	Pomacentrus sp1	-	10	10
	Pomacentrus sp2	-	5	5
	Pomacentrus spp	-	635	635
	Pomacentrus vaiuli	1090	195	1285
	Pomachromis richardsoni	605	120	725
	Stegastes fasciolatus	1790	175	1965
	Stegastes spp	-	75	75
Pseudochromidae	*Labracinus cyclophthalmus*	5	-	5
Scaridae	*Cetoscarus bicolor*	8	6	14
	Chlorurus bleekeri	11	1	12
	Chlorurus microrhinos	32	11	43
	Chlorurus sordidus	197	168	365
	Hipposcarus longiceps	40	19	59
	Scarus altipinnis	3	1	4
	Scarus chameleon	2	-	2
	Scarus dimidiatus	8	3	11
	Scarus flavipectoralis	11	-	11
	Scarus forsteni	37	2	39
	Scarus frenatus	25	12	37
	Scarus ghobban	2	-	2
	Scarus globiceps	4	-	4
	Scarus niger	26	11	37
	Scarus oviceps	5	-	5
	Scarus prasiognathos	1	-	1
	Scarus psittacus	9	-	9
	Scarus rubroviolaceus	10	1	11
	Scarus schlegeli	1	-	1
	Scarus spinus	3	1	4
	Scarus spp	-	29	29
Serranidae	*Aethaloperca rogaa*	12	3	15
	Anyperodon leucogrammicus	2	1	3
	Cephalopholis argus	56	28	84
	Cephalopholis miniata	3	-	3
	Cephalopholis spp	-	1	1

	Cephalopholis urodeta	25	9	34
	Epinephelus fuscoguttatus	1	-	1
	Epinephelus merra	4	-	4
	Epinephelus panamensis	2	-	2
	Epinephelus polyphekadion	1	-	1
	Epinephelus spp	-	1	1
	Plectropomus areolatus	1	-	1
	Plectropomus laevis	3	-	3
	Plectropomus oligacanthus	71	-	71
	Plectropomus spp	-	1	1
	Pseudanthias squamipinnis	61	26	87
	Pseudanthias tuka	347	805	1152
	Variola louti	2	-	2
Siganidae	*Siganus argenteus*	2	-	2
	Siganus doliatus	-	2	2
	Siganus puellus	2	-	2
	Siganus vulpinus	8	2	10
Tetraodontidae	*Arothron hispidus*	2	-	2
	Arothron stellatus	1	-	1
Zanclidae	*Zanclus cornutus*	87	77	164
Unknown	Unknown	-	9	9
Total	310	70280	45830	116110

5. SEDIMENT HYDROCARBON ANALYSES

5.1 Introduction/Background on 2010 observations

The S6 (Coral Reefs) subcomponent of the PTTEPAA/Dept. of SEWPaC *Monitoring Plan for the Montara Well Release Timor Sea* was undertaken by the Australian Institute of Marine Science (AIMS) in 2010. A sub-component of this involved the collection and analyses of fifty reef sediment samples from the reefs at Ashmore, Cartier and Seringapatam. Hydrocarbons were detected at multiple sites, but in the sediment samples with higher hydrocarbon levels, five samples were found at Ashmore Reef and one at each of Cartier Reef and Seringapatam Reef. More detailed analysis of the samples at Ashmore and Cartier Reefs (using Gas Chromatography Mass Spectroscopy, GCMS) indicated the presence of degraded crude oil. Based on this chemical evidence of a degraded crude oil (not bunker C or light diesel) above the ambient background concentrations for the Timor Sea, and the observations of surface slicks or sheens near the shallow reefs during the spill event by AMSA, it was considered reasonable to conclude that Ashmore Reef and, to a lesser degree Cartier Reef were contaminated by the Montara uncontrolled release. Follow-up surveys were recommended to PTTEPAA, and the sediment sampling component of S6 (Coral Reefs) was essentially repeated in 2011. The results are presented here.

5.2 Methods

5.2.1 Site selection

Between 28 February and 10 May 2011, 51 duplicate, surficial (upper 0-2 cm) sediment samples were collected from the shallow reef environments (1-6 m water depth) at Ashmore Reef (n=22 samples. Figure 5.1A), Cartier Reef (n = 15 samples, Figure 5.1B) and Seringapatam Reef (n=14 samples, Figure 5.1C).

5.2.2 Sample collection/handling

All samples were collected by SCUBA divers, allowing retrieval of undisturbed sediments using non-contaminated utensils. Samples were collected in separate pre-labelled, glass jars with Teflon®-lined caps, and kept frozen until analysis at the organic geochemistry laboratory at the AIMS (Townsville). All glassware, Teflon and stainless steel implements used in collection and analysis were thoroughly cleaned and rinsed in GCMS grade solvents.

5.2.3 Laboratory analyses

One of the duplicate samples at each location were selected for extraction and by scanning with Ultraviolet Fluorescence (UV/F) analysis (UNEP, 1992). Samples were defrosted overnight (by placing in a refrigerator) and seawater overlaying sediment was pipetted into a glass tube with Teflon lined screw cap. Two mL of hexane solvent was added to this water and used to extract any hydrocarbons that may have been dissolved off the sediments during freezing. Sandy 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 weighed into a 250 mL beaker and had approximately two to three times the wet weight of pre-combusted 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 in dichloromethane (DCM) was added to start the extraction. Surrogate standards (OTP or orthoterphenyl and C22:1) were added to track recovery. 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.

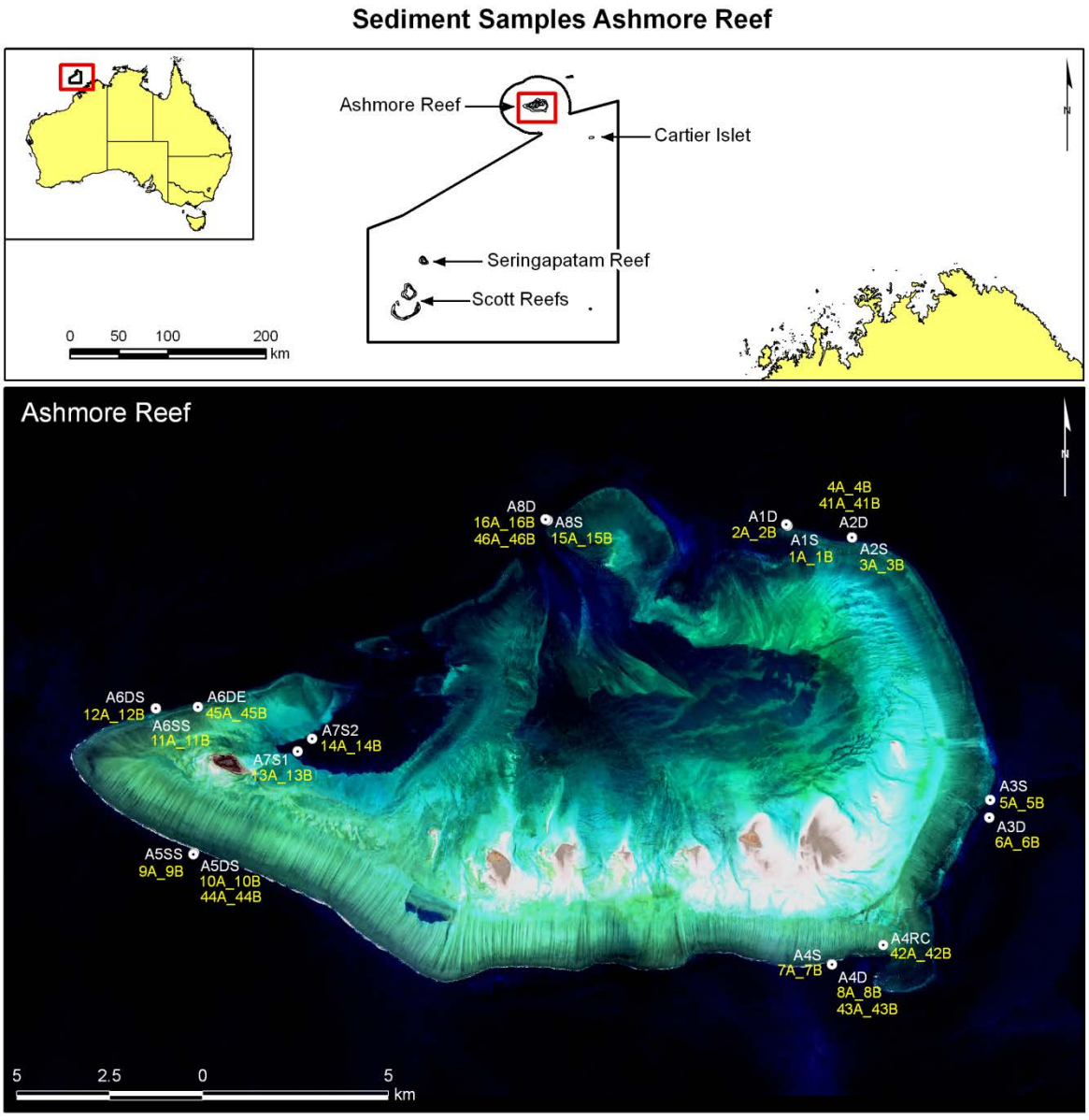


Figure 5.1A. Location map showing the sediment sampling locations at Ashmore Reef in 2011. Sediment samples were collected either at the Start (S) and/or End (E) of the coral monitoring survey locations. A = Ashmore, D = Deep (i.e. 5-6 m depth), S = shallow (i.e. 1-3 m depth), RC = Reef crest (1 m depth), yellow numbers refer to individual samples, and A and B refer to duplicate samples taken at each location.

Bottles were sonicated for an average of forty mins. 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 then 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 solvent and cleaned on a mini column of 1 g Al_2O_3 to remove some of the interfering biogenic pigments. Hydrocarbons were eluted off the alumina with 2 mL hexane followed by 2 mL DCM. Extracts had a few grains of pure newly precipitated copper added to bind sulphur (S8), which interferes with GCMS analysis. Samples then sat over night in a refrigerator to allow time to remove sulphur.

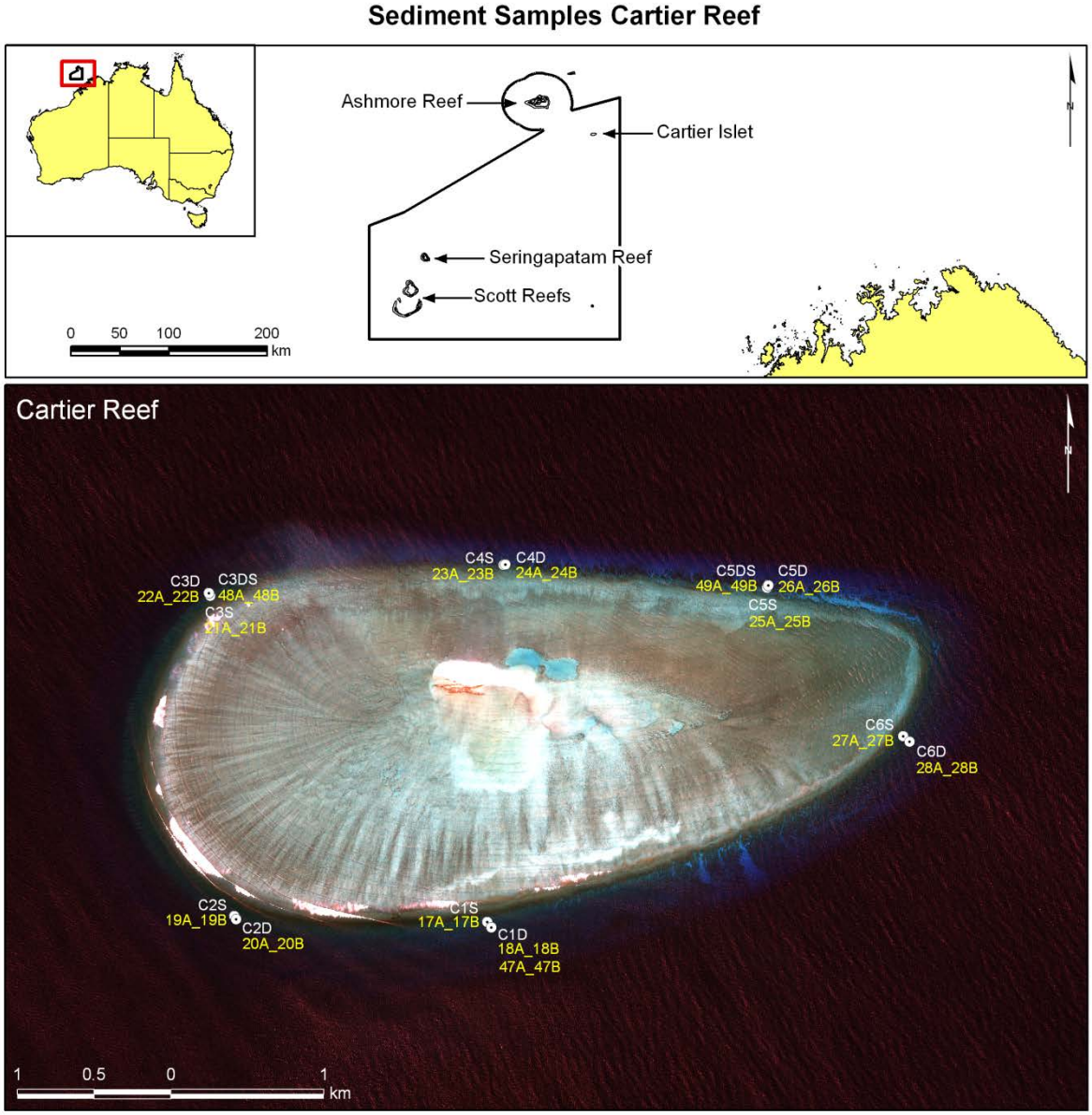


Figure 5.1B. Location map showing the sediment sampling locations at Cartier Reef in 2011. Sediment samples were collected either at the Start (S) and/or End (E) of the coral monitoring survey locations. C = Cartier, D = Deep (i.e. 5-6 m depth), S = Shallow (i.e. 1-3 m depth), RC = Reef crest (1 m depth), yellow numbers refer to individual samples, and A and B refer to duplicate samples taken at each location.

Extracts were then pipetted through another mini filter into a second tube followed by appropriate tube rinses. Extracts were then adjusted to 1 mL with N_2 gas for UVF analysis. Complete procedural blanks were obtained by extraction of 30 g of pre-combusted sodium sulfate. The Hitachi UV fluorometer was calibrated against a standard of 'Montara oil' sourced from Trevor Bastow at CSIRO. A sample of NAPL (non-aqueous phase liquid) from an oil/water sample recovered by fishermen from one of the Montara oil slicks was given to WA Fisheries. This was sent to Trevor Bastow at CSIRO for confirmation and then on to the AIMS laboratory as a reference sample. The NAPL oil was made up to concentrations of 0.2 mg/mL for UVF analysis and 1.0 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 cuvette.

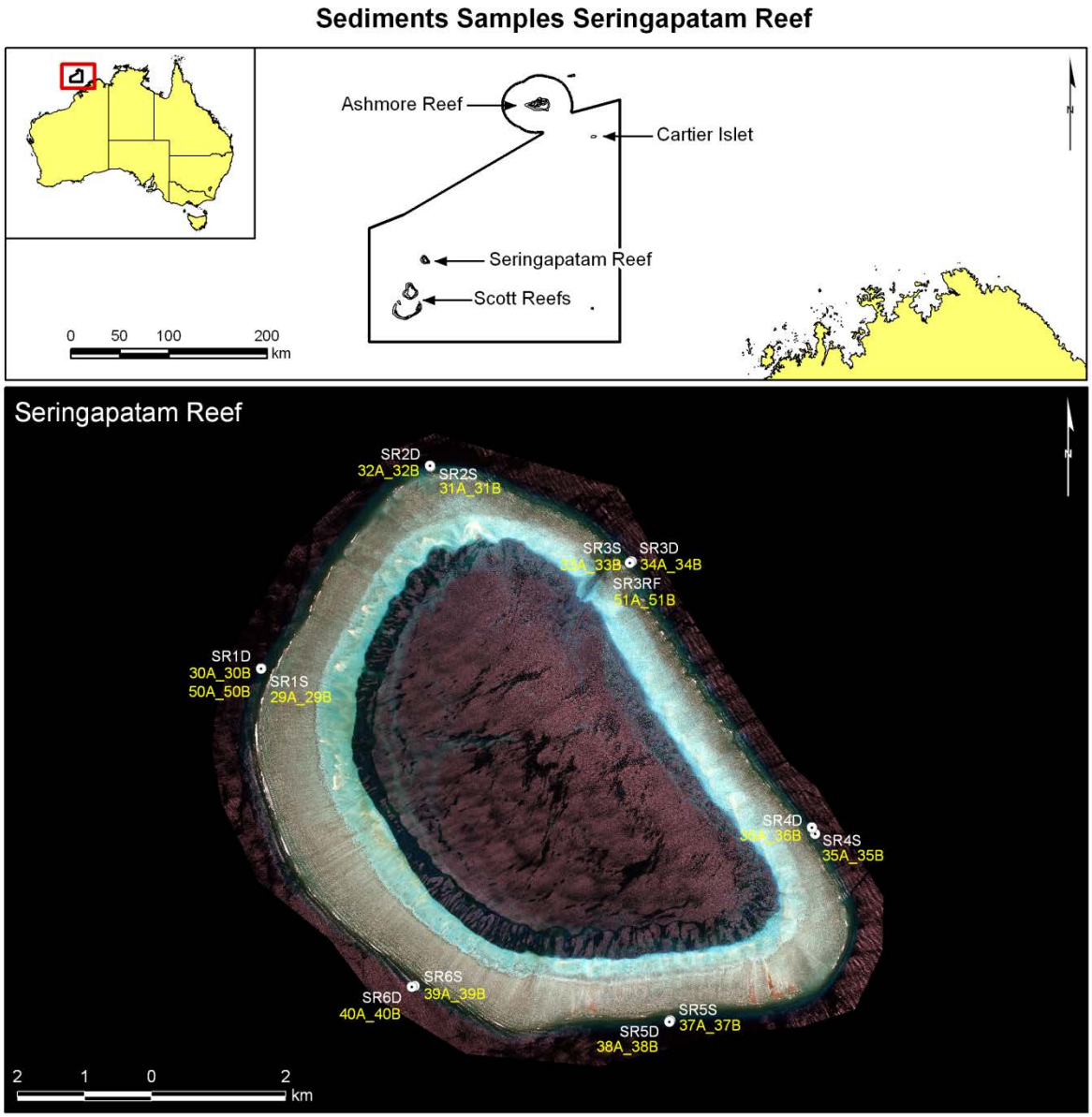


Figure 5.1C. Location map showing the sediment sampling locations at Seringapatam Reef in 2011. Sediment samples were collected either at the Start (S) and/or End (E) of the coral monitoring survey locations. SR = Seringapatam Reef, D = Deep (i.e. 5-6 m depth), S = Shallow (i.e. 1-3 m depth), RC = Reef crest (1 m depth), yellow numbers refer to individual samples, and A and B refer to duplicate samples taken at each location.

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 excitation/ 360 nm emission. 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 amounts of oil listed in the UVF Table 5.3 are based on the lower wavelength measurements plus the higher wavelength measurements. Amounts are expressed as µg oil per g dry weight.

Samples were judged positive when they had at least 3 times the blank values. Five samples (10% of all samples) that had detectable oil by UVF were selected for 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 SCAN/SIM program.

The reference NAPL oil was analysed along with the sediment samples. This is a starting point for interpretation of the sediment extracts.

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.

5.3 Results and Discussion

Table 5.1 contains the results of UVF analysis of the 51 extracts. Hydrocarbon concentrations above the detection limits (<~0.03 µg/g) were detected in 18 of the 51 samples (35%) ranging from 0.05 µg/g DW to a maximum of 0.38 µg/g DW (Table 5.1). At Ashmore Reef, hydrocarbons were detected in 7 of the 22 samples (32%) and at 5 of the 8 sampling locations (range 0.04 – 0.38 µg/g DW, Table 5.1, Figure 5.1A). There was no obvious relationship with the presence of hydrocarbons and water depth. At Cartier Reef, hydrocarbons were detected in 6 of the 15 samples (40%) and at 4 of the 6 sampling locations (range 0.05 – 0.12 µg/g DW, Table 5.1, Figure 5.1B). There was no obvious relationship with the presence of hydrocarbons and water depth. At Seringapatam Reef, hydrocarbons were detected in 5 of the 14 samples (36%) and at 3 of the 6 sampling locations, (range 0.05 – 0.09 µg/g, Table 5.1, Figure 5.1C). There was also no obvious relationship with the presence of hydrocarbons and water depth.

Table 5.1. Petroleum oil content (µg/g dry weight) of surficial (upper 0-2 cm) sediment samples collected by SCUBA divers from Ashmore Reef, Cartier Reef and Seringapatam Reef between 28 February 2011 and 10 May 2011, based on UVF analysis (sum of two wavelength measurements). ND = non-detectable. For sample and site locations see Figures 5.1A-C. Bold samples were selected for subsequent analysis by GCMS (see text and Table 5.3). Depth (m) refers to water depth in metres at the time of sampling.

Sample	Collection Date	Site	Depth (m)	Latitude (S) and Longitude (E)		UVF Oil (µg/g)
2AB	02-Mar	Ashmore 1D	6	-12.184	123.105	ND
1A	02-Mar	Ashmore 1S	3	-12.185	123.105	ND
4A	02-Mar	Ashmore 2D	6	-12.187	123.121	ND
41A	02-Mar	Ashmore 2D	6	-12.187	123.121	0.06
3AB	02-Mar	Ashmore 2S	3	-12.188	123.121	ND
6A	25-Feb	Ashmore 3D	6	-12.256	123.155	ND
5A	28-Feb	**Ashmore 3S**	3	-12.251	123.155	**0.23**
8A	28-Feb	Ashmore 4D	6	-12.291	123.116	ND
43B	28-Feb	Ashmore 4D	6	-12.291	123.116	ND
42B	28-Feb	Ashmore 4RC	1	-12.287	123.129	ND
7A	28-Feb	Ashmore 4S	3	-12.291	123.116	ND
10AB	07-May	Ashmore 5DS	6	-12.265	122.958	ND
44AB	07-May	Ashmore 5DS	6	-12.265	122.958	0.04
9B	07-May	Ashmore 5SS	3	-12.264	122.958	ND
45B	08-May	**Ashmore 6DE**	6	-12.229	122.959	**0.20**
12B	08-May	**Ashmore 6DS**	6	-12.229	122.949	**0.25**
11AB	08-May	Ashmore 6SS	3	-12.229	122.949	ND
13B	03-Mar	Ashmore 7S1	3	-12.240	122.984	ND
14A	03-Mar	Ashmore 7S2	3	-12.236	122.987	ND
16B	03-Mar	Ashmore 8D	6	-12.183	123.045	ND
46A	03-Mar	Ashmore 8D	6	-12.183	123.045	0.05
15A	03-Mar	**Ashmore 8S**	3	-12.183	123.046	**0.38**
18A	05-Mar	Cartier 1D	6	-12.545	123.556	ND
47A	05-Mar	Cartier 1D	6	-12.545	123.556	0.09
17A	05-Mar	Cartier 1S	3	-12.545	123.556	ND
20B	07-Mar	Cartier 2D	6	-12.545	123.541	ND
19B	07-Mar	Cartier 2S	3	-12.545	123.540	ND
22B	07-Mar	Cartier 3D	6	-12.526	123.539	ND
48B	10-May	Cartier 3DS	6	-12.526	123.539	0.05
21AB	07-Mar	Cartier 3S	3	-12.526	123.539	ND
24B	08-Mar	Cartier 4D	6	-12.524	123.557	ND
23AB	08-Mar	Cartier 4S	3	-12.524	123.557	ND
26A	07-Mar	Cartier 5D	6	-12.525	123.572	ND
49B	10-May	Cartier 5DS	6	-12.525	123.572	0.05
25A	07-Mar	**Cartier 5S**	3	-12.525	123.572	**0.12**
28A	05-Mar	Cartier 6D	6	-12.534	123.581	0.06
27A	05-Mar	Cartier 6S	3	-12.534	123.581	0.10
30A	08-Mar	Seringapatam 1D	6	-13.651	121.974	ND
50B	08-Mar	Seringapatam 1D	6	-13.651	121.974	ND
29B	08-Mar	Seringapatam 1S	3	-13.651	121.974	ND
32B	08-Mar	Seringapatam 2D	6	-13.624	121.998	0.09
31AB	08-Mar	Seringapatam 2S	3	-13.624	121.998	0.06
34A	09-Mar	Seringapatam 3D	6	-13.637	122.026	0.07
51A	10-Mar	Seringapatam 3RF	2	-13.637	122.025	ND
33B	09-Mar	Seringapatam 3S	3	-13.637	122.026	0.07
36A	08-Mar	Seringapatam 4D	6	-13.673	122.050	ND
35AB	08-Mar	Seringapatam 4S	3	-13.673	122.051	ND
38A	10-Mar	Seringapatam 5D	6	-13.699	122.031	ND
37B	10-Mar	Seringapatam 5S	3	-13.699	122.031	0.05
40A	10-Mar	Seringapatam 6D	6	-13.694	121.995	ND

39A	10-Mar	Seringapatam 6S	3	-13.694	121.995	ND

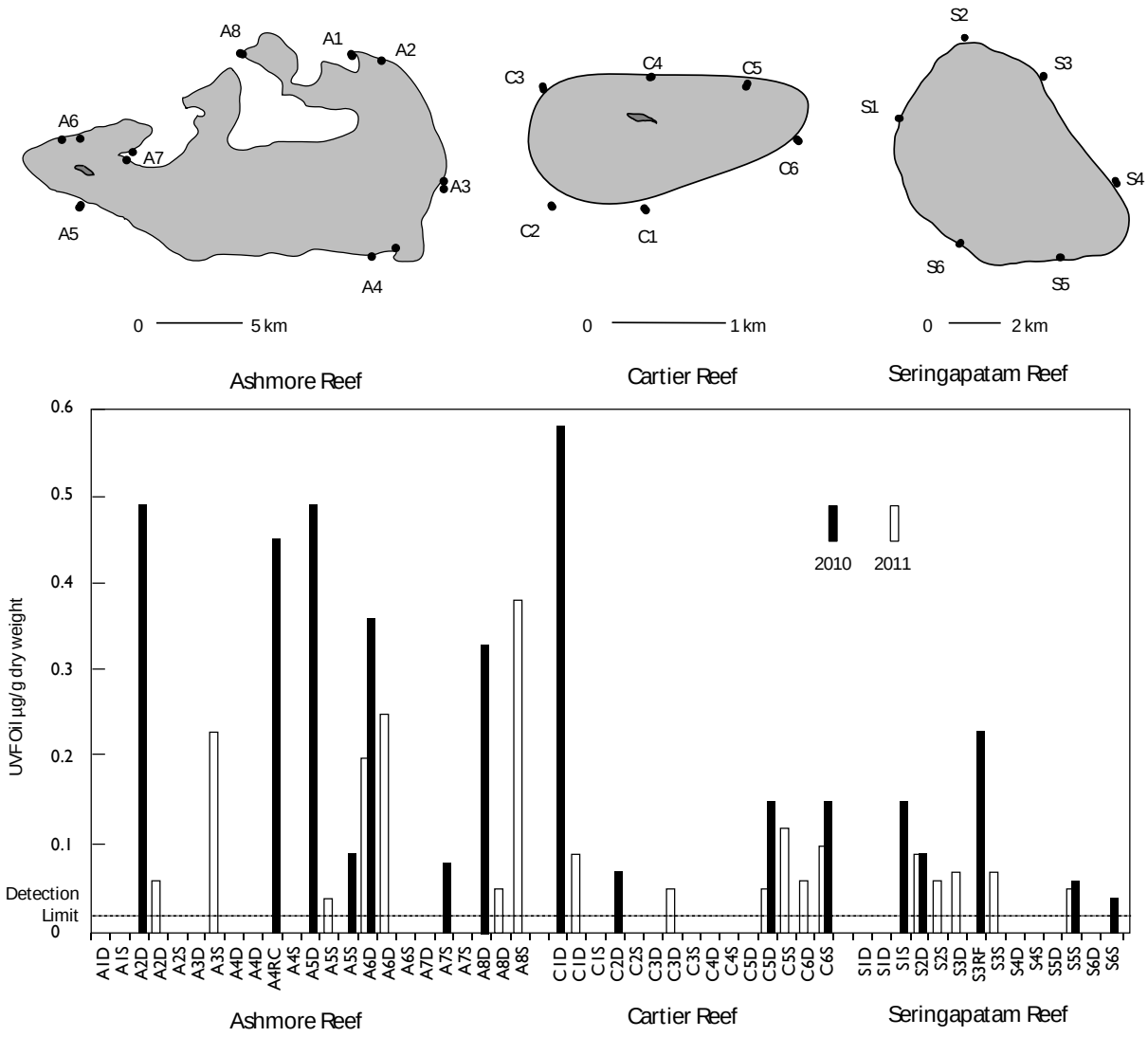


Figure 5.2. Petroleum oil content (µg/g dry weight) of surficial (upper 0-2 cm) sediment samples collected by SCUBA divers from Ashmore Reef, Cartier Reef and Seringapatam Reef in April 2010 based on lower wavelength UVF emission. Samples from 28 February 2011 to 10 May 2011, were based on the sum of the two wavelength UVF measurements). Detection limit is ~0.03 µg/g dry weight. For sample and site locations see Figure 5.1 A-C. Note: In 2010 several sediment samples were collected from the shoreline at Ashmore Reef and from Scott Reef and since repeat sampling from these locations was not conducted in 2011 the data has been excluded from the analyses.

Figure 5.2 shows the results from the 2011 sampling (present study) compared with the results from the previous year (sampled in April 2010). Results from the 2010 and 2011 surveys were broadly similar, showing petroleum hydrocarbons in the sandy sediments at multiple sites at each of the three locations and evidence of higher concentrations at Ashmore Reef than at Cartier Reef and Seringapatam Reef.

In 2010 ~50% of the sediment samples had petroleum hydrocarbon concentrations greater than the method detection limit, as compared to ~35% in 2011 (Figure 5.2, Table 5.2). In addition to the overall reduction in the number of sites with hydrocarbon concentration above the detection limit, there was a reduction in the measured hydrocarbon concentrations, with levels in 2011; ~60% of

levels in 2010 at Ashmore Reef, ~50% of levels measured in 2010 at Cartier Reef, ~71% of levels measured in and 2010 at Seringapatam Reef. Overall, for samples above the method detection limits, the mean hydrocarbon concentration in 2011 was 0.11 ± 0.09a (n = 18), or ~60% of the levels recorded in 2010 (0.11 ± 0.09 n = 18)(Table 5.2).

Based on the results of UVF analysis (see Table 5.1), the 5 sediment samples containing the highest hydrocarbon concentrations were selected for GCMS analysis to detail this continuing degradation process.

The sediments selected were coral sands containing shell debris and had total organic carbon values ranging from 0.25 to 0.67% of dry weight. The organic carbon to nitrogen ratios indicated the carbon was primarily of marine origin with values near 7 (Table 5.3).

Table 5.2. Comparison between petroleum hydrocarbon concentrations in 2010 versus 2011, showing the mean ± SD of sediments where hydrocarbon concentrations (as µg/g dry weight) exceeded the method detection limits, the number of sites sampled, and % of all sites (%Cont.) where hyrdocarbons were detected.

	2010			2011		
	Mean ± SD	Total	%Cont.	Mean	Total	%Cont.
All sites	0.19 ± 0.18 n = 22	45	49	0.11 ± 0.09 n = 18	51	35
Ashmore Reef	0.29 ± 0.18 n = 7	16	44	0.17 ±0.13 n = 7	22	32
Cartier Reef	0.16 ± 0.19 n = 7	17	41	0.08 ±0.03 n = 6	15	40
Seringapatam Reef	0.10 ± 0.07 n = 8	12	67	0.07 ± 0.01 n = 5	14	36

Table 5.3. Summary hydrocarbon data determined by GCMS of five sediment samples identified by the UVF analysis as having the highest hydrocarbon concentrations (see Table 5.1). TOC and the C/N ratios are also listed.

Sample Location	A8S	A3S	A6DS	A6DE	C5S
Sample Number	15A	5A	12B	45B	25A
Dry Wt Extracted (g)	24.0	23.4	19.9	21.5	22.9
% Total Organic Carbon	**0.25**	**0.26**	**0.67**	**0.47**	**0.38**
Molecular Organic C/N ratio	6.6	6.7	6.4	7.0	6.4
UVF Oil (µg/g)[1]	0.38	0.23	0.25	0.20	0.12
Total Hydrocarbons (µg/g)	1.26	0.33	2.05	2.60	0.57
%UCM	37.2	7.5	32.9	28.0	36.0
Total n-Alkanes C12-C38 (ng/g)	1909	57	2860	1262	197
∑ Oil PAHs (ng/g)[2]	1.8	2.4	11.2	9.4	3.4
∑ Combustion PAHs (ng/g)[3]	0.01	0.04	0.17	0.21	0.09
∑ Triterpanes (ng/g)[4]	265.0	59.3	161.2	nd	nd
∑ Steranes (ng/g)[4]	24.6	nd	226.1	nd	nd
Diploptene (ng/g)[5]	2.2	9.4	79.6	81.8	26.3
DBT / C4N ratio[6]	1.194	2.095	3.960	1.897	3.793

Notes:
UVF analysis is the sum of the 280 nm / 330 nm plus 310 nm / 360 nm measurements;
Oil PAHs is the sum of the naphthalene/biphenyl, phenanthrene/anthracene, fluorene, dibenzothiophene, pyrene, and chrysene/benzanthracene parent and alkylated aromatic hydrocarbon classes;
Combustion PAHs is the sum of high molecular weight PAHs including benzo(ae)pyrenes, dibenzanthracene, benzo(ghi perylene, and benzo(bk)fluoranthenes;
Triterpanes and steranes is a series of petroleum marker compounds;
Diploptene is a biomarker indicating residues of sulphate reducing bacteria;
DBT/C4N ratio was proposed to identify Montara crude oil. Ratio goes up with weathering as DBT is more persistent than the naphthalene series.

Total Hydrocarbons Concentrations (THC) ranged from 0.3 to 2.6 µg/g (Table 5.3). Significant amounts of the THC were unresolved complex material (UCM) typical of residual petroleum (Peters and Moldowan, 1993). The sum of oil Polycyclic Aromatic Hydrocarbons (PAHs) (see notes in Table 5.3) ranged from 1.8 to11.2 ng/g (ppb)(Table 5.3).

As discussed in the 2010 study, Liu et al. (2005) proposed the ratio of DBT/1367C4-Naphthalene might be a good diagnostic ratio to distinguish the Montara oil from other light oils on the North West Shelf. Analysis of the reference oil and extracting the m/z 184 ion for computing the ratio of DBT to 1367C4N showed the ratio was 0.61 on the AIMS GCMS system in 2011. The ratios of DBT/C4N of the degraded patterns was much higher than the oil standard (Table 5.3); which is to be expected. DBT is much more persistent in crude oiled sediments than the naphthalene series (Burns and Yelle-Simmons, 1995). Thus the ratio goes up with weathering and therefore this ratio cannot be used to identify the degraded Monatara oil.

Tables 5.4 and 5.5 contain the PAH and biomarker data calculated for the 5 sediment extracts analysed by GCMS. All five samples contained significant amounts of diploptene which is a biomarker for sulphate reducing bacteria known to be hydrocarbon degraders.

All the extracts contained a suite of PAHs, sterane and triterpane biomarkers expected for a degraded crude oil (Tables 5.4-5.5). Within each PAH group the higher molecular weight alkyl substituted compounds became more predominant as more of the lower molecular weight compounds had been removed by natural weathering processes.

Table 5.4. Petroleum PAHs in five sediment samples identified by the UVF analysis as having the highest hydrocarbon concentrations (see Tables 1and 2, and Figure 1.1 for sample locations and sample numbers). Values are pg/g dry wt except for the NAPL which is pg/uL oil .

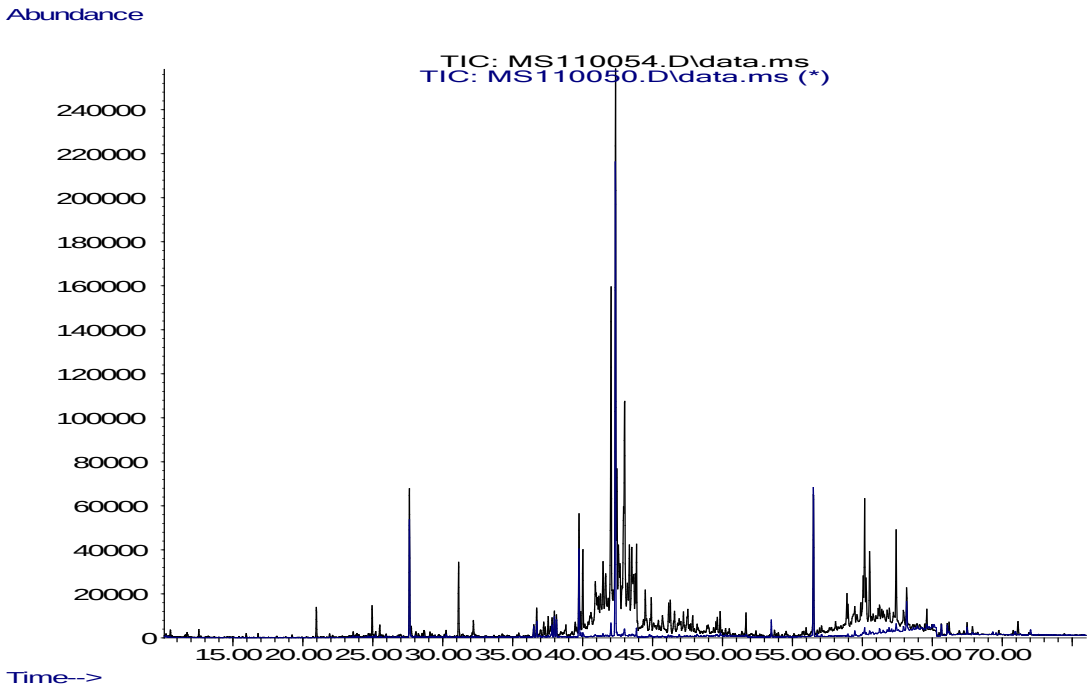
Sample number Sample site	pg/uL NAPL	CR 15A A8S	CR 5A AS3	CR 12B A6DS	CR 45B A6DE	CR 25A C5S
O-terphenyl SS (% recovery)		93	104	97	90	110
naphthalene	1139	184	459	383	368	292
C1-naphthalenes	9931	247	576	987	879	492
C2-napthalenes	29460	255	510	1171	5216	558
C3-naphthalenes	20373	41	111	495	183	213
C4-naphthalenes	17389	43	153	1105	877	633
biphenyl	749	<DL	115	162	176	96
C1-biphenyls	729	39	86	124	58	59
C2-biphenyls	2424	26	45	123	119	60
acenaphthylene	<DL	30	43	54	42	36
acenaphthene	50	6	25	188	145	58
fluorene	606	22	38	83	48	44
C1-fluorenes	763	14	100	216	196	258
C2-fluorenes	1226	150	26	282	102	93
DBT	672	11	12	28	<DL	17
C1-DBTs	718	<DL	<DL	<DL	<DL	<DL
C2-DBTs	2014	19	<DL	67	<DL	<DL
C3-DBTs	988	40	<DL	86	<DL	<DL
phenanthrene	2385	<DL	<DL	259	<DL	<DL
anthracene	18	18	22	52	40	29
C1-phenanthrenes/anthracenes	2020	125	29	298	<DL	42
C2-phenanthrenes/anthracenes	3716	51	<DL	493	150	15
C3-phenanthrenes/anthracenes	1864	10	7	117	11	<DL
C4-phenanthrenes/anthracenes	963	116	2	158	81	12
fluoranthene	18	<DL	<DL	127	72	63
pyrene	33	<DL	<DL	252	97	135
C1-fluoranthenes/pyrenes	199	43	26	131	33	34
C2-fluoranthenes/pyrenes	309	22	6	59	32	31
C3-fluoranthenes/pyrenes	115	7	3	20	37	10
benz(a)anthracene	12	<DL	<DL	<DL	<DL	<DL
chrysene	37	<DL	<DL	<DL	<DL	<DL

C1-benz(a)anthracenes/chrysenes	182	17	1	124	38	17
C2-benz(a)anthracenes/chrysenes	162	6	5	1999	162	13
C3-benz(a)anthracenes/chrysenes	63	152	2	1218	58	13
C4-benz(a)anthracenes/chrysenes	22	57	7	336	132	33
benzo(b)fluoranthene	30	<DL	<DL	<DL	<DL	<DL
benzo(k)fluoranthene	1	<DL	<DL	10	18	6
benzo(e)pyrene	28	<DL	27	66	77	42
benzo(a)pyrene	29	<DL	<DL	<DL	<DL	<DL
perylene	<DL	<DL	<DL	<DL	<DL	<DL
indeno(1,2,3-cd)pyrene	<DL	<DL	<DL	31	36	16
dibenz(a,h)anthracene	<DL	<DL	<DL	14	26	5
benzo(ghi)perylene	<DL	6	14	47	50	24

Table 5.5. Individual biomarkers for petroleum and hydrocarbon degradation in five sediment samples identified by the UVF analysis as having the highest hydrocarbon concentrations (see Tables 1 and 2, and Figure 1.1 for sample locations and sample numbers). Values are pg/g dry wt except for the NAPL which is pg/µL oil.

Sample Number	NAPL	15A	5A	12B	45B	25A
Sample Location	(pg/µL)	A8S	AS3	A6DS	A6DE	C5S
ß-cholane SS (%recovery)	NR	87	94	108	122	119
diploptene	<DL	2204	9401	79600	81805	26311
fluorenone	<DL	<DL	<DL	<DL	<DL	<DL
Ts C27 22,29,30 trisnorneohopane	24	39565	12794	24536	<DL	<DL
Tm C27 22,29,30-trisnorhopane	26	25090	12018	9358	<DL	<DL
C29H-17a,21B-30-norhopane	86	86213	<DL	61756	<DL	<DL
C30H-17a(H)21B(H)-hopane	93	114173	34505	65497	<DL	<DL
C31HS	47	<DL	<DL	<DL	<DL	<DL
C31HR	39	<DL	<DL	<DL	<DL	<DL
C32HS	27	<DL	<DL	<DL	<DL	<DL
C32HR	22	<DL	<DL	<DL	<DL	<DL
C33HS	13	<DL	<DL	<DL	<DL	<DL
C33HR	10	<DL	<DL	<DL	<DL	<DL
C27ba20S	3	<DL	<DL	131786	<DL	<DL
C27ba20R	2	<DL	<DL	33701	<DL	<DL
C27abb20R	13	<DL	<DL	25934	<DL	<DL
C27abb20S	8	3912	<DL	4990	<DL	<DL
C28abb20R	5	8280	<DL	9624	<DL	<DL
C28abb20S	5	<DL	<DL	13949	<DL	<DL
C29abb20R	15	12370	<DL	<DL	<DL	<DL

(A). Sample: 15A, Location: A8S. PAH SIM overlaid with Blank 1



(B). Sample: 15A, Location: A8S. NALK (Total Hydrocarbons) overlaid with Blank 1

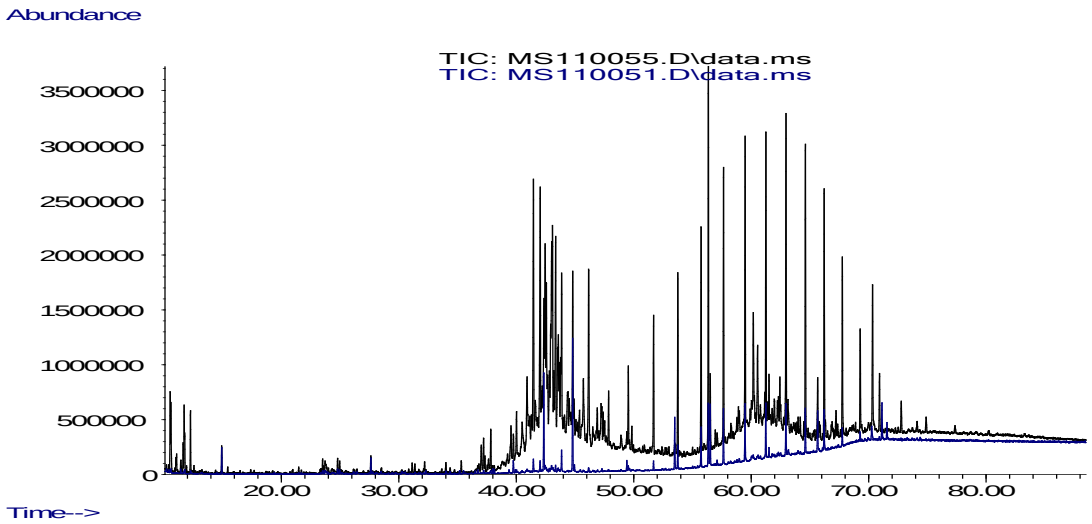
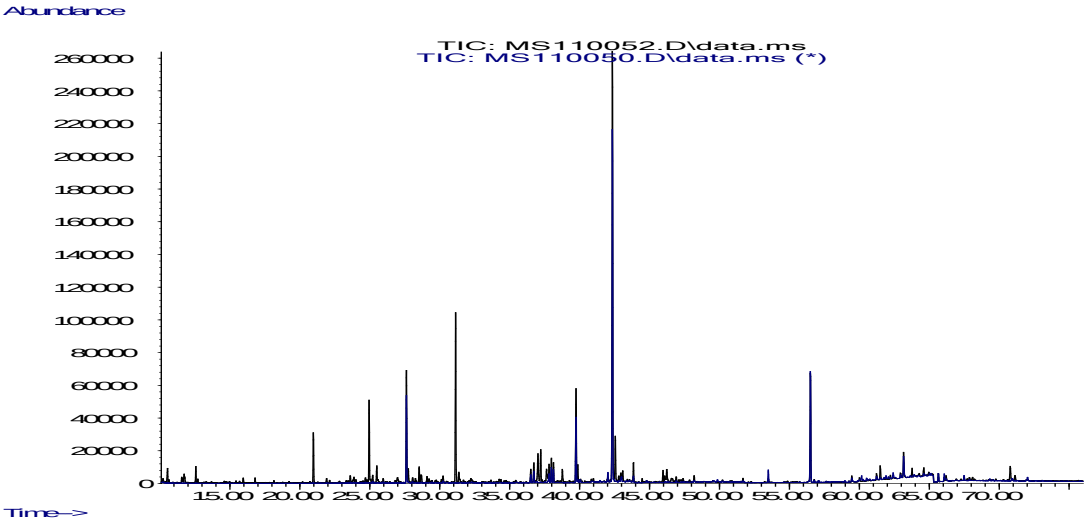


Figure 5.3 A, B. Reconstructed ion chromatograms for SIM PAHs and for full scan total hydrocarbons for five sediment samples identified by the UVF analysis as having the highest hydrocarbon concentrations (see Table 5.1 and Figure 5.1 for sample locations and sample numbers).

(C). Sample 5A, Location: AS3., PAHSIM overlaid with Blank 1.



(D). Sample 5A, Location AS3. NALK (Total Hydrocarbons) overlaid with Blank 1.

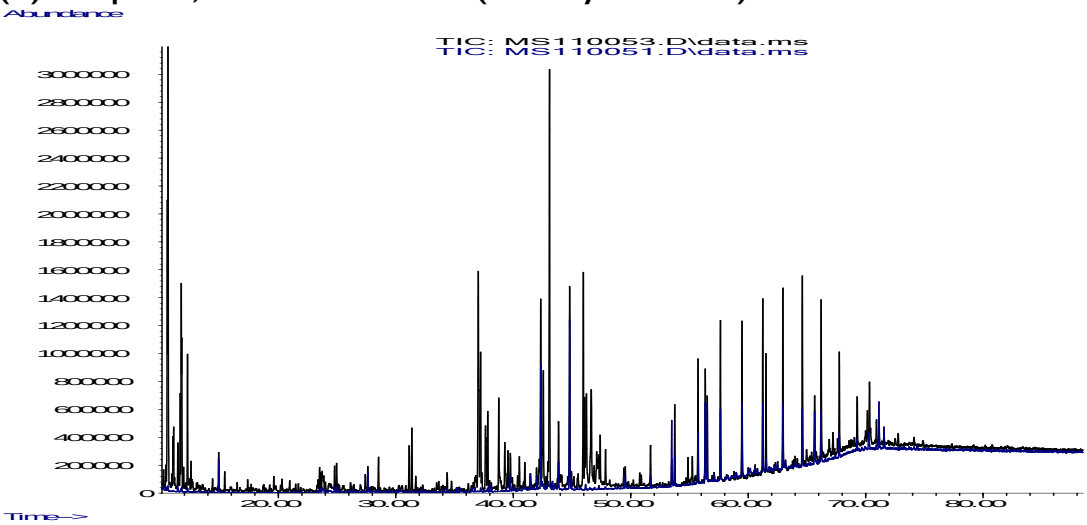
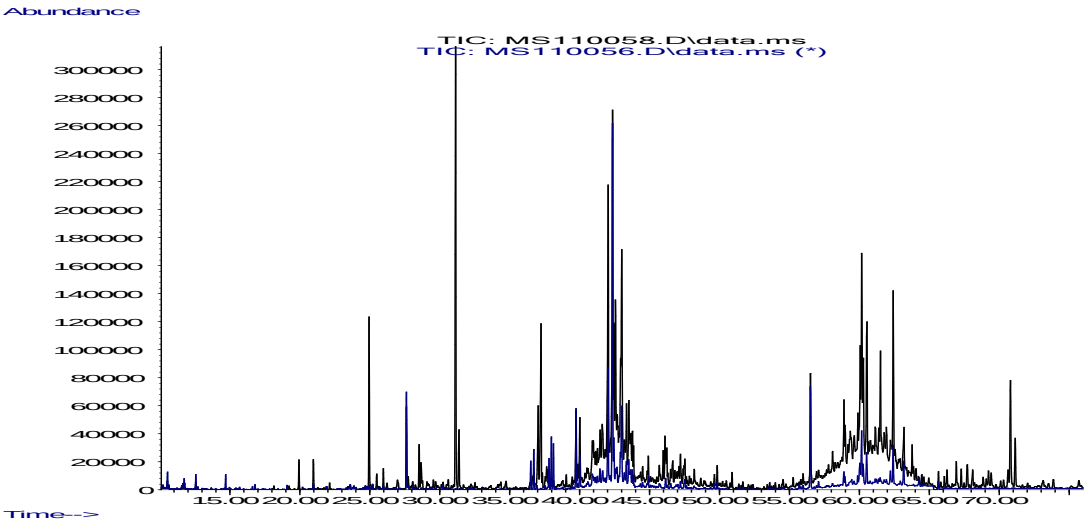


Figure 5.3 C,D. Reconstructed ion chromatograms for SIM PAHs and for full scan total hydrocarbons for five sediment samples identified by the UVF analysis as having the highest hydrocarbon concentrations (see Table 5.1 and Figure 5.1 for sample locations and sample numbers).

(E). Sample 12B, Location A6DS. PAHSIM overlaid with Blank 2



(F). Sample 12B, Location A6DS. NALK (Total Hydrocarbons) overlaid with Blank 2

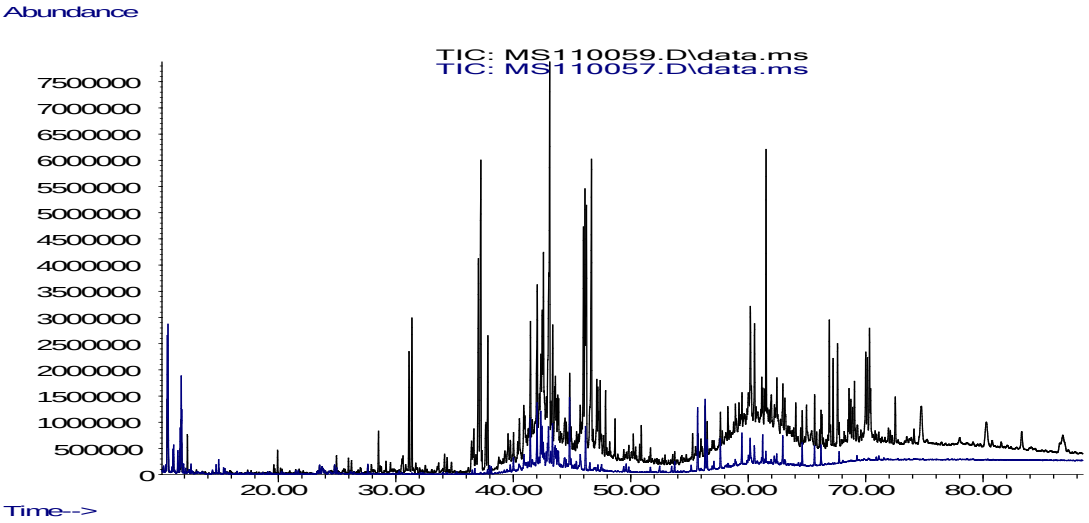
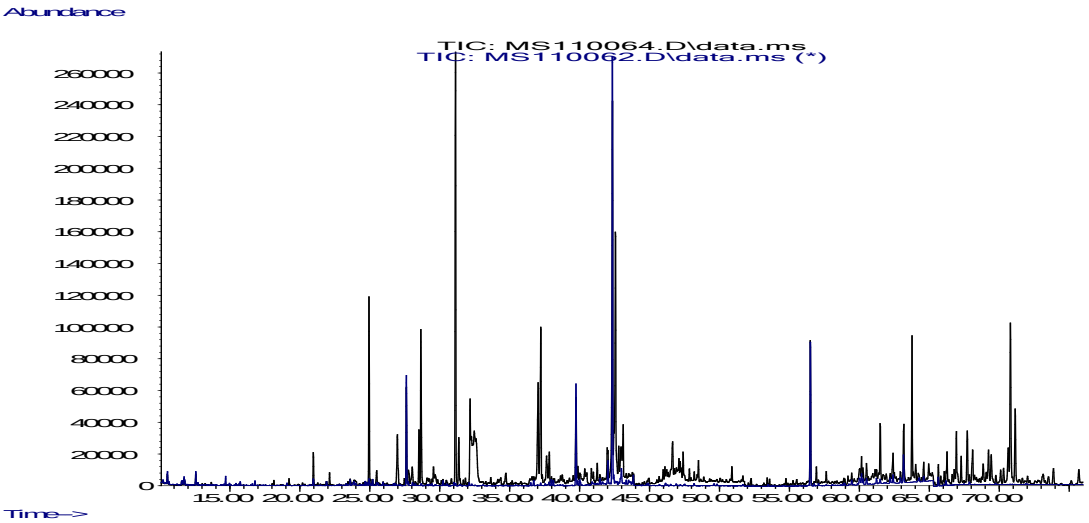


Figure 5.3 E, F. Reconstructed ion chromatograms for SIM PAHs and for full scan total hydrocarbons for five sediment samples identified by the UVF analysis as having the highest hydrocarbon concentrations (see Table 5.1 and Figure 5.1 for sample locations and sample numbers).

(G). Sample 45B, Location: A6DE. PAHSIM overlaid with Blank 3



(H). Sample 45B Location A6DE. NALK (Total Hydrocarbons) overlaid with Blank 3

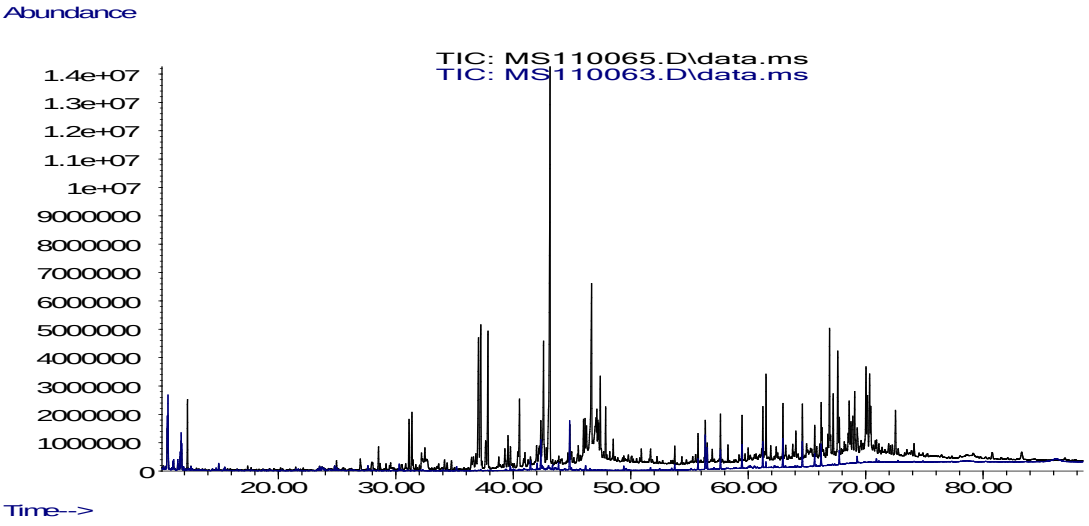
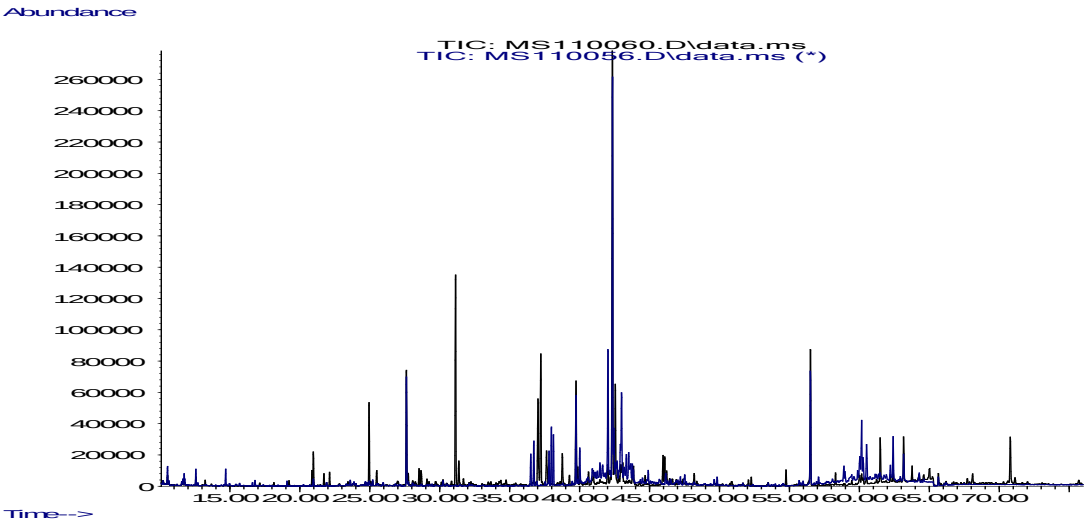


Figure 5.3 G, H. Reconstructed ion chromatograms for SIM PAHs and for full scan total hydrocarbons for five sediment samples identified by the UVF analysis as having the highest hydrocarbon concentrations (see Table 5.1 and Figure 5.1 for sample locations and sample numbers).

(I). Sample 25A Location C5S. PAHSIM overlaid with Blank 2



(J). Sample 25A Locations C5S. NALK (Total Hydrocarbons) overlaid with Blank 2

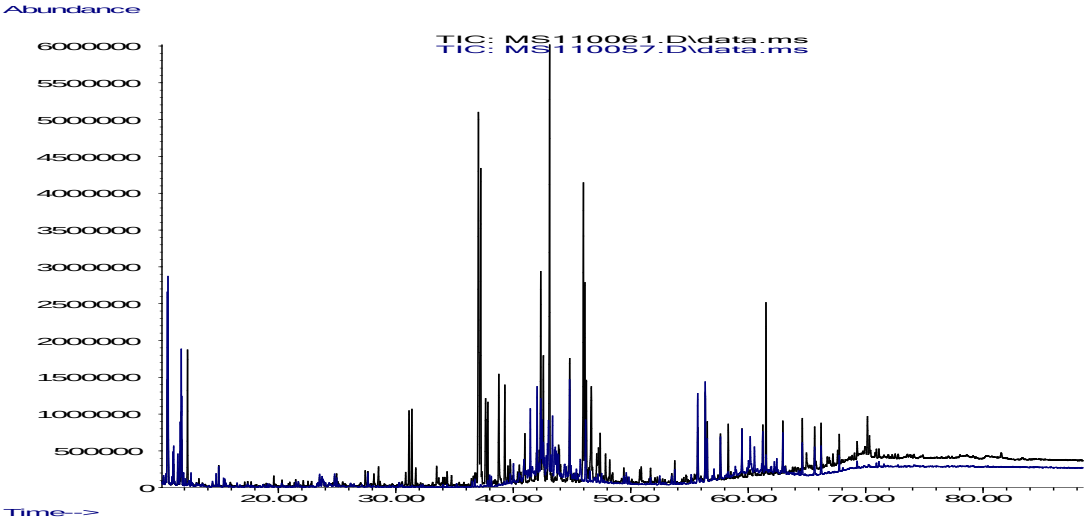


Figure 5.3 I, J. Reconstructed ion chromatograms for SIM PAHs and for full scan total hydrocarbons for five sediment samples identified by the UVF analysis as having the highest hydrocarbon concentrations (see Table 5.1 and Figure 5.1 for sample locations and sample numbers).

PAHs are widely accepted as toxic components of hydrocarbons (Neff and Anderson 1981). Interim Sediment Quality Guidelines (I-SQGs) are available for PAHs in Australia and New Zealand (see ANZECC/ARMCANZ 2000 and Simpson et al. 2005), based on guidelines developed in the US (see Long et al. 1995, Donald et al. 1996, see also Buchman 2008). Table 5.6 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 5.7. Parent and alkylated PAHs (ng/g DW normalized to 1% TOC) in the five sediment samples compared with sediment toxicity guidelines for Australia published by Simpson et al., (2005).

Sample number	15A	5A	12B	45B	25A	ISQG	ISQG
Sample site	A8S	AS3	A6DS	A6DE	C5S	Low	High
			pg/g			ng/g	
naphthalene	0.74	1.77	0.57	0.78	0.77	160	2,100
C1-naphthalenes	0.99	2.22	1.47	1.87	1.29		
acenaphthylene	0.12	0.17	0.08	0.09	0.09	44	640
acenaphthene	0.02	0.10	0.28	0.31	0.15	16	500
fluorene	0.09	0.15	0.12	0.10	0.12	19	540
phenanthrene	-	-	0.39	-	-	240	1,500
anthracene	0.07	0.08	0.08	0.09	0.08	85	1100
∑ LMW PAHs	2.03	4.47	2.99	3.24	2.50	552	3160
fluoranthene	-	-	0.19	0.15	0.17	600	5100
pyrene	-	-	0.38	0.21	0.36	665	2600
benz(a)anthracene	-	-	-	-	-	261	1,600
chrysene	-	-	-	-	-	384	2,800
benzo(a)pyrene	-	-	-	-	-	430	1,600
dibenz(a,h)anthracene	-	-	0.02	0.06	0.01	63	260
∑ HMW PAHs	-	-	0.59	0.41	0.53	1,700	9,600
∑ LMW and HMW PAHs	2.03	4.47	4.17	4.07	3.57	4,000	45,000

The US EPA (2003) also has based guidelines on a tested equilibrium model and the guidelines include many of the full suite of alkyl substituted aromatic hydrocarbons common in petroleum products. Table 5.7 has the values of PAHs in the reef sediments converted to $\mu g/g_{oc}$ and converted to Equilibrium Partitioning Sediment Benchmark Toxicity Units based on the guidelines published by the EPA. The number of compounds in the guidelines is limited to 34. The sum listed in Table 5.7 shows the sum (Σ) for the 34 PAHs and the sum (Σ) of total PAHs 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 the reef sediments are well below the toxic threshold.

Table 5.8. 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 5.4 were normalized to the TOC content of the sediments listed in Table 5.3 and divided by the EPA threshold for toxicity. ESBTU is the Equilibrium Partitioning Sediment Benchmark Final Toxic Unit with the data normalized to the organic carbon content of the sediment. The toxic concentration factors listed in bold are taken from EPA 2003. Since more PAHs were measured the non-bold factors for those compounds were estimated from similar structures, such as biphenyls and naphthalenes. Summary values approaching 1 are considered toxic (see text).

Sample number Sample site	15A A8S $ESBTU_{foc}$	5A AS3 $ESBTU_{foc}$	12B A6DS $ESBTU_{foc}$	45B A6DE $ESBTU_{foc}$	25A C5S $ESBTU_{foc}$	EPA $C_{oc,pah,vcv}$ ug/g_{oc}
naphthalene[a]	0.00019	0.00046	0.00015	0.00020	0.00020	**385**
C1-naphthalenes[a]	0.00022	0.00050	0.00033	0.00042	0.00029	**444**
C2-naphthalenes	0.00020	0.00038	0.00034	0.00218	0.00029	**510**
C3-naphthalenes	0.00003	0.00007	0.00013	0.00007	0.00010	**581**
C4-naphthalenes	0.00003	0.00009	0.00025	0.00028	0.00025	**657**
Biphenyl		0.00011	0.00006	0.00010	0.00007	385
C1-biphenyl	0.00004	0.00007	0.00004	0.00003	0.00004	444
C2-biphenyl	0.00002	0.00003	0.00004	0.00005	0.00003	510
acenaphthylene[a]	0.00003	0.00004	0.00002	0.00002	0.00002	**452**
acenaphthene[a]	0.00000	0.00002	0.00006	0.00006	0.00003	**491**
fluorene[a]	0.00002	0.00003	0.00002	0.00002	0.00002	**538**
C1-fluorenes	0.00001	0.00007	0.00006	0.00007	0.00012	**581**
C2-fluorenes	0.00009	0.00001	0.00006	0.00003	0.00004	**686**
DBT		0.00001	0.00001	0.00000	0.00001	594
C1-DBT		0.00000	0.00000	0.00000	0.00000	670
C2-DBT	0.00001	0.00000	0.00001	0.00000	0.00000	746
C3-DBT	0.00002	0.00000	0.00002	0.00000	0.00000	769
phenanthrene[a]	0.00000	0.00000	0.00006	0.00000	0.00000	
anthracene[a]	0.00001	0.00001	0.00001	0.00001	0.00001	**598**
C1-phen/anthr	0.00007	0.00002	0.00007	0.00000	0.00002	**594**
C2-phen/anthr	0.00003	0.00000	0.00010	0.00004	0.00001	**670**
C3-phen/anthr	0.00001	0.00000	0.00002	0.00000	0.00000	**746**
C4-phen/anthr	0.00005	0.00000	0.00003	0.00002	0.00000	**769**
fluoranthene[b]	0.00000	0.00000	0.00003	0.00002	0.00002	**913**
pyrene[b]	0.00000	0.00000	0.00005	0.00003	0.00005	**707**
C1-pyr/flouran	0.00002	0.00001	0.00003	0.00001	0.00001	**697**
C2-pyr/fluoran		0.00000	0.00001	0.00001	0.00001	**770**
C3-pyr/fluoran		0.00000	0.00000	0.00001	0.00000	860
benz(a)anthracene[b]	0.00000	0.00000	0.00000	0.00000	0.00000	949
chrysene[b]	0.00000	0.00000	0.00000	0.00000	0.00000	**841**
C1-benzan/chrys	0.00001	0.00000	0.00002	0.00001	0.00000	**844**
C2-benzan/chrys	0.00000	0.00000	0.00030	0.00003	0.00000	**929**
C3-benzan/chrys	0.00005	0.00000	0.00016	0.00001	0.00000	**1008**
C4-benzan/chrys	0.00002	0.00000	0.00004	0.00002	0.00001	**1112**
benzo(b)fluoranthene	0.00000	0.00000	0.00000	0.00000	0.00000	**1214**
benzo(k)fluoranthene	0.00000	0.00000	0.00000	0.00000	0.00000	**979**
benzo(e)pyrene	0.00000	0.00001	0.00001	0.00002	0.00001	**981**
benzo(a)pyrene	0.00000	0.00000	0.00000	0.00000	0.00000	**967**
perylene	0.00000	0.00000	0.00000	0.00000	0.00000	**965**
indeno(1,2,3-cd)pyrene	0.00000	0.00000	0.00000	0.00001	0.00000	**967**
dibenz(a,h)anthracene[b]	0.00000	0.00000	0.00000	0.00000	0.00000	**1115**
benzo(ghi)perylene	0.00000	0.00000	0.00000	0.00001	0.00001	**1123**
∑All	0.00118	0.00197	0.00255	0.00381	0.00168	
∑EPA34	0.00109	0.00174	0.00236	0.00362	0.00152	

5.4 Conclusions

Studies of hydrocarbon concentrations in sediments at Ashmore, Cartier and Seringapatam Reefs in 2010 (conducted five months after the discharge of oil and gas from the Montara well ceased) showed concentrations above detection limits in ~49% of samples, generally low hydrocarbon levels, and a pattern of greater hydrocarbon levels at Ashmore and Cartier reefs (see S6 Coral Reefs, Heyward et al. 2010). In the present survey (S6B Coral Reefs), conducted ~15 months after the discharge ceased, hydrocarbons recorded in fewer samples (35%), and the petroleum hydrocarbon levels were lower, but there was still a pattern of greater hydrocarbon concentrations at Ashmore Reef.

The GCMS analyses (Table 5.3) and reconstructed ion chromatogram analyses (Figures 5.3 A-J) showed the hydrocarbons had patterns typical of degraded oil, including a bimodal distribution (as also seen in the 2010 study). In 2011, the sediments had high concentrations of diploptene (the biomarker for sulfate reducing bacteria that are known to degrade hydrocarbons, Tables 5.3 and 5.4) and the sterane and triterpane biomarkers expected for a degraded crude oil (Table 5.4). Collectively these results are consistent with weathering processes which have changed concentrations and chromatogram patterns.

Oil was observed at Ashmore Reef during the uncontrolled release, and given the higher presence of hydrocarbons there (as compared with the more distantly located Seringapatam Reef), the pattern is suggestive of contamination from the uncontrolled release. However, given the degraded state of the oil, it was not possible to accurately identify the hydrocarbon components (i.e. to source match) and hence to unequivocally link the hydrocarbons at Ashmore Reef to the Montara uncontrolled release. Previous studies in the Timor Sea and Northwest Shelf have shown there is a background presence of petroleum hydrocarbons (Burns et al 2001, 2010) which could originate from natural seeps, the oil industry, passing ships or discharge from fishing boats.

Irrespective of the source, normalization of the PAH component of the oil to total organic carbon allowed direct comparison to Australian and USEPA sediment quality assessment guidelines (SQGS). In both 2010 and 2011, concentrations of PAHs in the sediments were well below the guideline levels at the time of sampling.

In the event of future uncontrolled releases, sampling and analysis of sediment for hydrocarbons should be undertaken immediately. Since sampling only occurred five months (S6 Coral Reef) and 15 months (S6B Coral Reef) after the Montara well was capped, it is unlikely that the true extent of any possible contamination of the shallow water sediments of the emergent reef systems of the Timor Sea will ever be known.

5.5 References

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6. Appendix - Metadata summary of all sampling site locations

Date	Time	Technique	Site	Sample	Lat_start	Long_start	Depth
11/2/11		Tile	A1	see Montara Settlement Plate database V1.3	-12.1842	123.1047	6
11/2/11		Tile	A2	see Montara Settlement Plate database V1.3	-12.1874	123.1211	6
11/2/11		Tile	A3	see Montara Settlement Plate database V1.3	-12.2555	123.1550	6
11/2/11		Tile	A4	see Montara Settlement Plate database V1.3	-12.2914	123.1161	6
12/2/11		Tile	A5	see Montara Settlement Plate database V1.3	-12.2645	122.9580	6
12/2/11		Tile	A6	see Montara Settlement Plate database V1.3	-12.2291	122.9488	6
12/2/11		Tile	A7	see Montara Settlement Plate database V1.3	-12.2396	122.9839	3
13/2/11		Tile	A8	see Montara Settlement Plate database V1.3	-12.1830	123.0452	6
13/2/11		Tile	C1	see Montara Settlement Plate database V1.3	-12.5455	123.5559	6
13/2/11		Tile	C6	see Montara Settlement Plate database V1.3	-12.5355	123.5800	6
14/2/11		Tile	C5	see Montara Settlement Plate database V1.3	-12.5253	123.5725	6
14/2/11		Tile	C4	see Montara Settlement Plate database V1.3	-12.5241	123.5567	6
14/2/11		Tile	C3	see Montara Settlement Plate database V1.3	-12.5258	123.5389	6
14/2/11		Tile	C2	see Montara Settlement Plate database V1.3	-12.5451	123.5405	6
15/2/11		Tile	S3	see Montara Settlement Plate database V1.3	-13.6366	122.0256	6
15/2/11		Tile	S2	see Montara Settlement Plate database V1.3	-13.6236	122.9978	6
15/2/11		Tile	S5	see Montara Settlement Plate database V1.3	-13.6988	122.0305	6
15/2/11		Tile	S4	see Montara Settlement Plate database V1.3	-13.6726	122.0503	6
16/2/11		Tile	S6	see Montara Settlement Plate database V1.3	-13.6939	121.9950	6
16/2/11		Tile	S1	see Montara Settlement Plate database V1.3	-13.6509	121.9744	6
16/2/11		Tile	SS2	see Montara Settlement Plate database V1.3	-13.9238	121.9152	6
16/2/11		Tile	SL3	see Montara Settlement Plate database V1.3	-14.0690	121.7767	6
17/2/11		Tile	SL1	see Montara Settlement Plate database V1.3	-14.0793	121.9474	6
17/2/11		Tile	SS1	see Montara Settlement Plate database V1.3	-14.0788	121.9783	6
17/2/11		Tile	SL2	see Montara Settlement Plate database V1.3	-14.1884	121.7989	6
25/2/11	10:30	Juvenile Coral	A3D	Montara Juvenile coral database V1.1	-12.2555	123.1550	6
25/2/11		Dove	A3D	MTA_A3D_LE_20110225152927	-12.2555	123.1550	6
25/2/11		Dove	A3D	MTA_A3D_LF_20110225152927_1	-12.2555	123.1550	6
25/2/11		Dove	A3D	MTA_A3D_LG_20110225152927_2	-12.2555	123.1550	6
25/2/11		Dove	A3D	MTA_A3D_RE_20110225152917	-12.2555	123.1550	6
25/2/11		Dove	A3D	MTA_A3D_RF_20110225152917_1	-12.2555	123.1550	6
25/2/11		Dove	A3D	MTA_A3D_RG_20110225152917_2	-12.2555	123.1550	6
25/2/11		Dove	A3D	MTA_A3D_LA_20110225133607	-12.2555	123.1550	6
25/2/11		Dove	A3D	MTA_A3D_LB_20110225133607_1	-12.2555	123.1550	6
25/2/11		Dove	A3D	MTA_A3D_LC_20110225133607_2	-12.2555	123.1550	6
25/2/11		Dove	A3D	MTA_A3D_LD_20110225133607_3	-12.2555	123.1550	6
25/2/11		Dove	A3D	MTA_A3D_RA_20110225133640	-12.2555	123.1550	6
25/2/11		Dove	A3D	MTA_A3D_RB_20110225133640_1	-12.2555	123.1550	6
25/2/11		Dove	A3D	MTA_A3D_RC_20110225133640_2	-12.2555	123.1550	6
25/2/11		Dove	A3D	MTA_A3D_RD_20110225133640_3	-12.2555	123.1550	6
25/2/11	15:00	Coral Collection	A3S	see Montara Coral Samples database V1.2	-12.2513	123.1553	3
25/2/11	14:30	Dive Transect	A3S	AIMS Reef Ecology database	-12.2513	123.1553	3
25/2/11	10:30	Juvenile Coral	A3S	Montara Juvenile coral database V1.1	-12.2513	123.1553	3
28/2/11	15:30	Coral Collection	A3D	see Montara Coral Samples database V1.2	-12.2555	123.1550	6
28/2/11	15:30	Coral Collection	A3N	see Montara Coral Samples database V1.2	-12.2510	123.1580	10
28/2/11		Sediment	A3S	5A_5B	-12.2513	123.1553	3
28/2/11	15:30	Coral Collection	A3S	see Montara Coral Samples database V1.2	-12.2513	123.1553	3
28/2/11		Dove	A3S	MTA_A3S_LA_20110301084129	-12.2513	123.1553	3
28/2/11		Dove	A3S	20110329083922	-12.2513	123.1553	3
28/2/11	10:00	Sediment	A4D	8A_8B	-12.2914	123.1161	6
28/2/11	10:00	Sediment	A4D	43A_43B	-12.2914	123.1161	6
28/2/11	11:00	Dove	A4D	MTA_A4D_LA_20110301110004	-12.2914	123.1161	6

28/2/11	11:05	Dove	A4D	MTA_A4D_LB_20110301110513	-12.2914	123.1161	6
28/2/11	10:58	Dove	A4D	MTA_A4D_RA_20110301105800	-12.2914	123.1161	6
28/2/11	11:03	Dove	A4D	MTA_A4D_RB_20110301110311	-12.2914	123.1161	6
28/2/11	16:00	Sediment	A4RC	42A_42B	-12.2865	123.1288	1
28/2/11	16:00	Sediment	A4S	7A_7B	-12.2913	123.1161	3
28/2/11	14:41	Dove	A4S	MTA_A4S_Apex_LA_20110301144126	-12.2913	123.1161	3
28/2/11	14:39	Dove	A4S	MTA_A4S_Apex_RA_20110301143958	-12.2913	123.1161	3
28/2/11	14:20	Dove	A4S	MTA_A4S_LA_20110301142020	-12.2913	123.1161	3
28/2/11	14:23	Dove	A4S	MTA_A4S_LB_20110301142351	-12.2913	123.1161	3
28/2/11	14:18	Dove	A4S	MTA_A4S_RA_20110301141833	-12.2913	123.1161	3
28/2/11		Dove	A4S	MTA_A4S_RB_20110303142216	-12.2913	123.1161	3
1/3/11		Juvenile Coral	A4D	Montara Juvenile coral database V1.1	-12.2914	123.1161	6
1/3/11		Dive Transect	A4D	AIMS Reef Ecology database	-12.2914	123.1161	6
1/3/11		Juvenile Coral	A4S	Montara Juvenile coral database V1.1	-12.2913	123.1161	3
1/3/11		Dive Transect	A4S	AIMS Reef Ecology database	-12.2913	123.1161	3
2/3/11		Sediment	A1D	2A_2B	-12.1842	123.1047	6
2/3/11		Dive Transect	A1D	AIMS Reef Ecology database	-12.1842	123.1047	6
2/3/11		Juvenile Coral	A1S	Montara Juvenile coral database V1.1	-12.1846	123.1052	3
2/3/11		Sediment	A1S	1A_1B	-12.1846	123.1052	3
2/3/11		Dove	A1S	MTA_A1S_Apex_LA_20110302152144	-12.1846	123.1052	3
2/3/11		Dove	A1S	MTA_A1S_Apex_RA_20110302151946	-12.1846	123.1052	3
2/3/11		Dove	A1S	MTA_A1S_LA_20110302145354	-12.1846	123.1052	3
2/3/11		Dove	A1S	MTA_A1S_LB_20110302150057	-12.1846	123.1052	3
2/3/11		Dove	A1S	MTA_A1S_RA_20110302145143	-12.1846	123.1052	3
2/3/11		Dove	A1S	MTA_A1S_RB_20110302145857	-12.1846	123.1052	3
2/3/11		Dive Transect	A1S	AIMS Reef Ecology database	-12.1846	123.1052	3
2/3/11		Sediment	A2D	4A_4B	-12.1874	123.1211	6
2/3/11		Sediment	A2D	41A_41B	-12.1874	123.1211	6
2/3/11		Juvenile Coral	A2D	Montara Juvenile coral database V1.1	-12.1874	123.1211	6
2/3/11		Dove	A2D	MTA_A2D_Apex_LA_20110302112001	-12.1874	123.1211	6
2/3/11		Dove	A2D	MTA_A2D_Apex_RA_20110302111721	-12.1874	123.1211	6
2/3/11		Dove	A2D	MTA_A2D_LA_20110302103023	-12.1874	123.1211	6
2/3/11		Dove	A2D	MTA_A2D_LB_20110302105417	-12.1874	123.1211	6
2/3/11		Dove	A2D	MTA_A2D_RA_20110302102843	-12.1874	123.1211	6
2/3/11		Dove	A2D	MTA_A2D_RB_20110302105144	-12.1874	123.1211	6
2/3/11		Dive Transect	A2D	AIMS Reef Ecology database	-12.1874	123.1211	6
2/3/11		Sediment	A2S	3A_3B	-12.1875	123.1211	3
2/3/11		Juvenile Coral	A2S	Montara Juvenile coral database V1.1	-12.1875	123.1211	3
2/3/11		Coral Collection	A2S	see Montara Coral Samples database V1.2	-12.1875	123.1211	3
2/3/11		Dove	A2S	MTA_A2S_LA_20110302095339	-12.1875	123.1211	3
2/3/11		Dove	A2S	MTA_A2S_Apex_RA_20110302095132	-12.1875	123.1211	3
2/3/11		Dove	A2S	MTA_AS2_LA_20110302092652	-12.1875	123.1211	3
2/3/11		Dove	A2S	20110302093341	-12.1875	123.1211	3
2/3/11		Dove	A2S	MTA_A2S_RA_2011030292434	-12.1875	123.1211	3
2/3/11		Dove	A2S	MTA_A2S_RB_20110302093144	-12.1875	123.1211	3
2/3/11		Dive Transect	A2S	AIMS Reef Ecology database	-12.1875	123.1211	3
3/3/11		Dove	A1D	MTA_A1D_Apex_LA_20110303075251	-12.1842	123.1047	6
3/3/11		Dove	A1D	MTA_A1D_Apex_RA_20110303075015	-12.1842	123.1047	6
3/3/11		Dove	A1D	MTA_A1D_LA_20110303072026	-12.1842	123.1047	6
3/3/11		Dove	A1D	MTA_A1D_LB_20110303072847	-12.1842	123.1047	6
3/3/11		Dove	A1D	MTA_A1D_RA_20110303071800	-12.1842	123.1047	6
3/3/11		Dove	A1D	MTA_A1D_RB_20110303072648	-12.1842	123.1047	6
3/3/11		Juvenile Coral	A7S1	Montara Juvenile coral database V1.1	-12.2396	122.9839	3
3/3/11		Sediment	A7S1	13A_13B	-12.2396	122.9839	3
3/3/11		Dive Transect	A7S1	AIMS Reef Ecology database	-12.2396	122.9839	3
3/3/11		Coral Collection	A7S1	see Montara Coral Samples database V1.2	-12.2396	122.9839	3
3/3/11		Dove	A7S1	MTA_A71S_Apex_LA_20110303152707	-12.2396	122.9839	3
3/3/11		Dove	A7S1	MTA_A71S_Apex_RA_20110303152449	-12.2396	122.9839	3
3/3/11		Dove	A7S1	MTA_A71S_RA_20110303145930	-12.2396	122.9839	3

3/3/11		Dove	A7S1	MTA_A71S_RB_20110303150551	-12.2396	122.9839	3
3/3/11		Dove	A7S1	MTA_A71S_LA_20110303150203	-12.2396	122.9839	3
3/3/11		Dove	A7S1	MTA_A71S_LA_20110303150809	-12.2396	122.9839	3
3/3/11		Juvenile Coral	A7S2	Montara Juvenile coral database V1.1	-12.2364	122.9874	3
3/3/11		Sediment	A7S2	14A_14B	-12.2364	122.9874	3
3/3/11		Coral Collection	A7S2	see Montara Coral Samples database V1.2	-12.2364	122.9874	3
3/3/11		Coral Collection	A7S2	see Montara Coral Samples database V1.2	-12.2364	122.9874	3
3/3/11		Dove	A7S2	MTA_A72S_Apex_LA_20110303165208	-12.2364	122.9874	3
3/3/11		Dove	A7S2	MTA_A72S_Apex_RA_20110303164931	-12.2364	122.9874	3
3/3/11		Dove	A7S2	MTA_A72S_RA_20110303162012	-12.2364	122.9874	3
3/3/11		Dove	A7S2	MTA_A72S_RA_20110303162915	-12.2364	122.9874	3
3/3/11		Dove	A7S2	MTA_A72S_LA_20110303162246	-12.2364	122.9874	3
3/3/11		Dove	A7S2	MTA_A72S_LB_20110303163152	-12.2364	122.9874	3
3/3/11		Sediment	A8D	16A_16B	-12.1830	123.0452	6
3/3/11		Sediment	A8D	46A_46B	-12.1830	123.0452	6
3/3/11		Juvenile Coral	A8D	Montara Juvenile coral database V1.1	-12.1830	123.0452	6
3/3/11		Dive Transect	A8D	AIMS Reef Ecology database	-12.1830	123.0452	6
3/3/11		Dove	A8D	MTA_A8D_Apex_LA_20110303101138	-12.1830	123.0452	6
3/3/11		Dove	A8D	MTA_A8D_Apex_RA_20110303100858	-12.1830	123.0452	6
3/3/11		Dove	A8D	MTA_A8D_LA_20110303094702	-12.1830	123.0452	6
3/3/11		Dove	A8D	MTA_A8D_LB_20110303095515	-12.1830	123.0452	6
3/3/11		Dove	A8D	MTA_A8D_RA_20110303094428	-12.1830	123.0452	6
3/3/11		Dove	A8D	MTA_A8D_RB_20110303095234	-12.1830	123.0452	6
3/3/11		Juvenile Coral	A8S	Montara Juvenile coral database V1.1	-12.1833	123.0458	3
3/3/11		Sediment	A8S	15A_15B	-12.1833	123.0458	3
3/3/11		Dive Transect	A8S	AIMS Reef Ecology database	-12.1833	123.0458	3
3/3/11		Dove	A8S	MTA_A8S_Apex_LA_20110303120312	-12.1833	123.0458	3
3/3/11		Dove	A8S	MTA_A8S_Apex_RA_20110303120041	-12.1833	123.0458	3
3/3/11		Dove	A8S	MTA_A8S_LA_20110303113648	-12.1833	123.0458	3
3/3/11		Dove	A8S	MTA_A8S_LB_20110303114417	-12.1833	123.0458	3
3/3/11		Dove	A8S	MTA_A8S_RA_20110303113437	-12.1833	123.0458	3
3/3/11		Dove	A8S	MTA_A8S_RB_20110303114138	-12.1833	123.0458	3
4/3/11		Dive Transect	A7S2	AIMS Reef Ecology database	-12.2364	122.9874	3
4/3/11		Coral Collection	A7S2	see Montara Coral Samples database V1.2	-12.2364	122.9874	3
4/3/11		Coral Collection	C1D	see Montara Coral Samples database V1.2	-12.5455	123.5559	6
5/3/11		Sediment	C1D	18A_18B	-12.5455	123.5559	6
5/3/11		Sediment	C1D	47A_47B	-12.5455	123.5559	6
5/3/11		Dive Transect	C1D	AIMS Reef Ecology database	-12.5455	123.5559	6
5/3/11		Juvenile Coral	C1D	Montara Juvenile coral database V1.1	-12.5455	123.5559	6
5/3/11		Dove	C1D	20110305144239	-12.5455	123.5559	6
5/3/11		Dove	C1D	20110305144008	-12.5455	123.5559	6
5/3/11		Dove	C1D	20110305141457	-12.5455	123.5559	6
5/3/11		Dove	C1D	20110305142310	-12.5455	123.5559	6
5/3/11		Dove	C1D	20110305141238	-12.5455	123.5559	6
5/3/11		Dove	C1D	20110305142040	-12.5455	123.5559	6
5/3/11		Sediment	C1S	17A_17B	-12.5452	123.5556	3
5/3/11		Dive Transect	C1S	AIMS Reef Ecology database	-12.5452	123.5556	3
5/3/11		Juvenile Coral	C1S	Montara Juvenile coral database V1.1	-12.5452	123.5556	3
5/3/11		Dove	C1S	20110305161230	-12.5452	123.5556	3
5/3/11		Dove	C1S	20110305161617	-12.5452	123.5556	3
5/3/11		Dove	C1S	20110305161004	-12.5452	123.5556	3
5/3/11		Dove	C1S	20110305161354	-12.5452	123.5556	3
5/3/11		Dove	C1S	20110305153323	-12.5452	123.5556	3
5/3/11		Dove	C1S	20110305154737	-12.5452	123.5556	3
5/3/11		Dove	C1S	20110305153110	-12.5452	123.5556	3
5/3/11		Dove	C1S	20110305154513	-12.5452	123.5556	3
5/3/11		Coral Collection	C6D	see Montara Coral Samples database V1.2	-12.5345	123.5810	6
5/3/11		Sediment	C6D	28A_28B	-12.5345	123.5810	6
5/3/11		Dive Transect	C6D	AIMS Reef Ecology database	-12.5345	123.5810	6

5/3/11		Juvenile Coral	C6D	Montara Juvenile coral database V1.1	-12.5455	123.5559	6
5/3/11		Dove	C6D	20110305100738	-12.5455	123.5559	6
5/3/11		Dove	C6D	20110305100506	-12.5455	123.5559	6
5/3/11		Dove	C6D	20110305094434	-12.5455	123.5559	6
5/3/11		Dove	C6D	20110305094713	-12.5455	123.5559	6
5/3/11		Dove	C6D	20110305094215	-12.5455	123.5559	6
5/3/11		Dove	C6D	20110305094434	-12.5455	123.5559	6
5/3/11		Coral Collection	C6S	see Montara Coral Samples database V1.2	-12.5341	123.5806	3
5/3/11		Sediment	C6S	27A_27B	-12.5341	123.5806	3
5/3/11		Dive Transect	C6S	AIMS Reef Ecology database	-12.5341	123.5806	3
5/3/11		Juvenile Coral	C6S	Montara Juvenile coral database V1.1	-12.5341	123.5806	3
5/3/11		Dove	C6S	20110305112315	-12.5341	123.5806	3
5/3/11		Dove	C6S	20110305112105	-12.5341	123.5806	3
5/3/11		Dove	C6S	20110305104801	-12.5341	123.5806	3
5/3/11		Dove	C6S	20110305105304	-12.5341	123.5806	3
5/3/11		Dove	C6S	20110305104610	-12.5341	123.5806	3
5/3/11		Dove	C6S	20110305105059	-12.5341	123.5806	3
6/3/11		Coral Collection	C1E	see Montara Coral Samples database V1.2	-12.5430	123.4000	3
6/3/11		Juvenile Coral	C2D	Montara Juvenile coral database V1.1	-12.5451	123.5405	6
6/3/11		Dove	C2D	20110306102446	-12.5451	123.5405	6
6/3/11		Dove	C2D	20110306102247	-12.5451	123.5405	6
6/3/11		Dove	C2D	20110306100409	-12.5451	123.5405	6
6/3/11		Dove	C2D	20110306100733	-12.5451	123.5405	6
6/3/11		Dove	C2D	20110306100203	-12.5451	123.5405	6
6/3/11		Dove	C2D	20110306100458	-12.5451	123.5405	6
6/3/11		Juvenile Coral	C2S	Montara Juvenile coral database V1.1	-12.5449	123.5404	3
6/3/11		Coral Collection	C2S	see Montara Coral Samples database V1.2	-12.5449	123.5404	3
6/3/11		Dive Transect	C2S	AIMS Reef Ecology database	-12.5449	123.5404	3
6/3/11		Dove	C2S	20110306115316	-12.5449	123.5404	3
6/3/11		Dove	C2S	20110306115057	-12.5449	123.5404	3
6/3/11		Dove	C2S	20110306115052	-12.5449	123.5404	3
6/3/11		Dove	C2S	20110306114837	-12.5449	123.5404	3
6/3/11		Dove	C2S	20110306112020	-12.5449	123.5404	3
6/3/11		Dove	C2S	20110306112902	-12.5449	123.5404	3
6/3/11		Dove	C2S	20110306111821	-12.5449	123.5404	3
6/3/11		Dove	C2S	20110306112653	-12.5449	123.5404	3
6/3/11		Coral Collection	C5D	see Montara Coral Samples database V1.2	-12.5253	123.5725	6
6/3/11		Dive Transect	C5D	AIMS Reef Ecology database	-12.5253	123.5725	6
6/3/11		Juvenile Coral	C5D	Montara Juvenile coral database V1.1	-12.5253	123.5725	6
6/3/11		Dove	C5D	MTA_C5D_Apex_LA_20110306144920	-12.5253	123.5725	6
6/3/11		Dove	C5D	MTA_C5D_Apex_RA_20110306144649	-12.5253	123.5725	6
6/3/11		Dove	C5D	MTA_C5D_LA_20110306142152	-12.5253	123.5725	6
6/3/11		Dove	C5D	MTA_C5D_LB_20110306142710	-12.5253	123.5725	6
6/3/11		Dove	C5D	MTA_C5D_RA_20110306141934	-12.5253	123.5725	6
6/3/11		Dove	C5D	MTA_C5D_RB_20110306142503	-12.5253	123.5725	6
6/3/11		Coral Collection	C5S	see Montara Coral Samples database V1.2	-12.5254	123.5724	3
6/3/11		Dive Transect	C5S	AIMS Reef Ecology database	-12.5254	123.5724	3
6/3/11		Juvenile Coral	C5S	Montara Juvenile coral database V1.1	-12.5254	123.5724	3
6/3/11		Dove	C5S	MTA_C5S_Apex_LA_2011030616737	-12.5254	123.5724	3
6/3/11		Dove	C5S	MTA_C5S_Apex_RA_2011030616533	-12.5254	123.5724	3
6/3/11		Dove	C5S	MTA_C5S_LA_20110306154714	-12.5254	123.5724	3
6/3/11		Dove	C5S	MTA_C5S_LB_20110306154732	-12.5254	123.5724	3
6/3/11		Dove	C5S	MTA_C5S_LC_20110306155551	-12.5254	123.5724	3
6/3/11		Dove	C5S	MTA_C5S_RA_20110306154550	-12.5254	123.5724	3
6/3/11		Dove	C5S	MTA_C5S_RB_20110306155315	-12.5254	123.5724	3
7/3/11		Sediment	C2D	20A_20B	-12.5451	123.5405	6
7/3/11		Dive Transect	C2D	AIMS Reef Ecology database	-12.5451	123.5405	6
7/3/11		Sediment	C2S	19A_19B	-12.5449	123.5404	3
7/3/11		Coral Collection	C3D	see Montara Coral Samples database V1.2	-12.5258	123.5389	6

7/3/11		Dive Transect	C3D	AIMS Reef Ecology database	-12.5258	123.5389	6
7/3/11		Juvenile Coral	C3D	Montara Juvenile coral database V1.1	-12.5258	123.5389	6
7/3/11		Sediment	C3D	22A_22B	-12.5258	123.5389	6
7/3/11		Dove	C3D	20110307162514	-12.5258	123.5389	6
7/3/11		Dove	C3D	20110307162600	-12.5258	123.5389	6
7/3/11		Dove	C3D	20110307162349	-12.5258	123.5389	6
7/3/11		Dove	C3D	20110307155243	-12.5258	123.5389	6
7/3/11		Dove	C3D	20110307160723	-12.5258	123.5389	6
7/3/11		Dove	C3D	20110307155030	-12.5258	123.5389	6
7/3/11		Dove	C3D	20110307160511	-12.5258	123.5389	6
7/3/11		Dive Transect	C3S	AIMS Reef Ecology database	-12.5260	123.5390	3
7/3/11		Juvenile Coral	C3S	Montara Juvenile coral database V1.1	-12.5260	123.5390	3
7/3/11		Sediment	C3S	21A_21B	-12.5260	123.5390	3
7/3/11		Dove	C3S	20110307145353	-12.5260	123.5390	3
7/3/11		Dove	C3S	20110307145121	-12.5260	123.5390	3
7/3/11		Dove	C3S	20110307142755	-12.5260	123.5390	3
7/3/11		Dove	C3S	20110307142810	-12.5260	123.5390	3
7/3/11		Dove	C3S	20110307143219	-12.5260	123.5390	3
7/3/11		Dove	C3S	20110307142616	-12.5260	123.5390	3
7/3/11		Dove	C3S	20110307142936	-12.5260	123.5390	3
7/3/11		Juvenile Coral	C4D	Montara Juvenile coral database V1.1	-12.5241	123.5567	6
7/3/11		Coral Collection	C4D	see Montara Coral Samples database V1.2	-12.5241	123.5567	6
7/3/11		Dove	C4D	MTA_C4D_Apex_LA_20110307101053	-12.5241	123.5567	6
7/3/11		Dove	C4D	MTA_C4D_Apex_RA_20110307100821	-12.5241	123.5567	6
7/3/11		Dove	C4D	MTA_C4D_LA_20110307093637	-12.5241	123.5567	6
7/3/11		Dove	C4D	MTA_C4D_LB_20110307094527	-12.5241	123.5567	6
7/3/11		Dove	C4D	MTA_C4D_RA_20110307093412	-12.5241	123.5567	6
7/3/11		Dove	C4D	MTA_C4D_RA_20110307094257	-12.5241	123.5567	6
7/3/11		Dive Transect	C4D	AIMS Reef Ecology database	-12.5241	123.5567	6
7/3/11		Coral Collection	C4S	see Montara Coral Samples database V1.2	-12.5241	123.5566	3
7/3/11		Juvenile Coral	C4S	Montara Juvenile coral database V1.1	-12.5241	123.5566	3
7/3/11		Dove	C4S	MTA_C4S_Apex_LA_20110307090947	-12.5241	123.5566	3
7/3/11		Dove	C4S	MTA_C4S_Apex_RA_20110307090736	-12.5241	123.5566	3
7/3/11		Dove	C4S	MTA_C4S_LA_20110307083844	-12.5241	123.5566	3
7/3/11		Dove	C4S	MTA_C4S_LB_20110307084011	-12.5241	123.5566	3
7/3/11		Dove	C4S	MTA_C4S_LC_20110307084613	-12.5241	123.5566	3
7/3/11		Dove	C4S	MTA_C4S_RA_20110307083625	-12.5241	123.5566	3
7/3/11		Dove	C4S	MTA_C4S_RB_20110307083735	-12.5241	123.5566	3
7/3/11		Dove	C4S	MTA_C4S_RC_20110307084353	-12.5241	123.5566	3
7/3/11		Dive Transect	C4S	AIMS Reef Ecology database	-12.5241	123.5566	3
7/3/11		Sediment	C5D	26A_26B	-12.5253	123.5725	6
7/3/11		Sediment	C5S	25A_25B	-12.5254	123.5724	3
8/3/11		Sediment	C4D	24A_24B	-12.5241	123.5567	6
8/3/11		Sediment	C4S	23A_23B	-12.5241	123.5566	3
8/3/11		Coral Collection	SR1D	see Montara Coral Samples database V1.2	-13.6509	121.9744	6
8/3/11		Dive Transect	SR1D	AIMS Reef Ecology database	-13.6509	121.9744	6
8/3/11		Juvenile Coral	SR1D	Montara Juvenile coral database V1.1	-13.6509	121.9744	6
8/3/11		Sediment	SR1D	30A_30B	-13.6509	121.9744	6
8/3/11		Sediment	SR1D	50A_50B	-13.6509	121.9744	6
8/3/11		Dove	SR1D	MTA_SR1D_Apex_LA_20110308163135	-13.6509	121.9744	6
8/3/11		Dove	SR1D	MTA_SR1D_Apex_RA_20110308162859	-13.6509	121.9744	6
8/3/11		Dove	SR1D	MTA_SR1D_LA_20110308160046	-13.6509	121.9744	6
8/3/11		Dove	SR1D	MTA_SR1D_LB_20110308161106	-13.6509	121.9744	6
8/3/11		Dove	SR1D	MTA_SR1D_RA_20110308160843	-13.6509	121.9744	6
8/3/11		Dove	SR1D	MTA_SR1D_RB_20110308155809	-13.6509	121.9744	6
8/3/11		Coral Collection	SR1S	see Montara Coral Samples database V1.2	-13.6509	121.9744	3
8/3/11		Dive Transect	SR1S	AIMS Reef Ecology database	-13.6509	121.9744	3
8/3/11		Juvenile Coral	SR1S	Montara Juvenile coral database V1.1	-13.6509	121.9744	3
8/3/11		Sediment	SR1S	29A_29B	-13.6509	121.9744	3

8/3/11		Dove	SR1S	MTA_SR1S_Apex_LA_20110308145835	-13.6509	121.9744	3
8/3/11		Dove	SR1S	MTA_SR1S_Apex_RA_20110308145604	-13.6509	121.9744	3
8/3/11		Dove	SR1S	MTA_SR1S_LA_20110308143215	-13.6509	121.9744	3
8/3/11		Dove	SR1S	MTA_SR1S_LB_20110308143858	-13.6509	121.9744	3
8/3/11		Dove	SR1S	MTA_SR1S_RA_20110308142957	-13.6509	121.9744	3
8/3/11		Dove	SR1S	MTA_SR1S_RB_20110308143600	-13.6509	121.9744	3
8/3/11		Sediment	SR2D	32A_32B	-13.6236	121.9978	6
8/3/11		Coral Collection	SR2D	see Montara Coral Samples database V1.2	-13.6236	121.9978	6
8/3/11		Dive Transect	SR2D	AIMS Reef Ecology database	-13.6236	121.9978	6
8/3/11		Juvenile Coral	SR2D	Montara Juvenile coral database V1.1	-13.6236	121.9978	6
8/3/11		Dove	SR2D	MTA_SR2D_Apex_LA_20110308103408	-13.6236	121.9978	6
8/3/11		Dove	SR2D	MTA_SR2D_Apex_RA_20110308103155	-13.6236	121.9978	6
8/3/11		Dove	SR2D	MTA_SR2D_LA_20110308100803	-13.6236	121.9978	6
8/3/11		Dove	SR2D	MTA_SR2D_LB_20110308101715	-13.6236	121.9978	6
8/3/11		Dove	SR2D	MTA_SR2D_RA_20110308100527	-13.6236	121.9978	6
8/3/11		Dove	SR2D	MTA_SR2D_RB_20110308101456	-13.6236	121.9978	6
8/3/11		Sediment	SR2S	31A_31B	-13.6237	121.9978	3
8/3/11		Dive Transect	SR2S	AIMS Reef Ecology database	-13.6237	121.9978	3
8/3/11		Juvenile Coral	SR2S	Montara Juvenile coral database V1.1	-13.6237	121.9978	3
8/3/11		Dove	SR2S	MTA_SR2S_Apex_LA_20110308091707	-13.6237	121.9978	3
8/3/11		Dove	SR2S	MTA_SR2S_Apex_RA_20110308091501	-13.6237	121.9978	3
8/3/11		Dove	SR2S	MTA_SR2S_LA_20110308085104	-13.6237	121.9978	3
8/3/11		Dove	SR2S	MTA_SR2S_LB_20110308085124	-13.6237	121.9978	3
8/3/11		Dove	SR2S	MTA_SR2S_LC_20110308085543	-13.6237	121.9978	3
8/3/11		Dove	SR2S	MTA_SR2S_RA_20110308084811	-13.6237	121.9978	3
8/3/11		Dove	SR2S	MTA_SR2S_RB_20110308085316	-13.6237	121.9978	3
8/3/11		Coral Collection	SR3D	see Montara Coral Samples database V1.2	-13.6366	122.0256	6
8/3/11		Sediment	SR4D	36A_36B	-13.6726	122.0503	6
8/3/11		Sediment	SR4S	35A_35B	-13.6735	122.0507	3
8/3/11		Coral Collection	SRN	see Montara Coral Samples database V1.2	-13.6272	121.9904	8
9/3/11		Sediment	SR3D	34A_34B	-13.6366	122.0256	6
9/3/11		Juvenile Coral	SR3D	Montara Juvenile coral database V1.1	-13.6366	122.0256	6
9/3/11		Dove	SR3D	MTA_SR3D_Apex_LA_20110309162748	-13.6366	122.0256	6
9/3/11		Dove	SR3D	MTA_SR3D_Apex_RA_20110309162513	-13.6366	122.0256	6
9/3/11		Dove	SR3D	MTA_SR3D_LA_20110309160433	-13.6366	122.0256	6
9/3/11		Dove	SR3D	MTA_SR3D_RA_20110309160209	-13.6366	122.0256	6
9/3/11		Dive Transect	SR3D	AIMS Reef Ecology database	-13.6366	122.0256	6
9/3/11		Coral Collection	SR3S	see Montara Coral Samples database V1.2	-13.6366	122.0256	3
9/3/11		Sediment	SR3S	33A_33B	-13.6366	122.0256	3
9/3/11		Juvenile Coral	SR3S	Montara Juvenile coral database V1.1	-13.6366	122.0256	3
9/3/11		Dove	SR3S	20110309150834	-13.6366	122.0256	3
9/3/11		Dove	SR3S	20110309150610	-13.6366	122.0256	3
9/3/11		Dove	SR3S	MTA_S3RS_LB_20110309144636	-13.6366	122.0256	3
9/3/11		Dove	SR3S	MTA_S3RS_LA_20110309143524	-13.6366	122.0256	3
9/3/11		Dove	SR3S	MTA_S3RS_RA_20110309143242	-13.6366	122.0256	3
9/3/11		Dove	SR3S	MTA_S3RS_RB_20110309144413	-13.6366	122.0256	3
9/3/11		Dive Transect	SR3S	AIMS Reef Ecology database	-13.6366	122.0256	3
9/3/11		Juvenile Coral	SR4D	Montara Juvenile coral database V1.1	-13.6726	122.0503	6
9/3/11		Dove	SR4D	20110309105053	-13.6726	122.0503	6
9/3/11		Dove	SR4D	MTA_SR4D_LA_20110309102552	-13.6726	122.0503	6
9/3/11		Dove	SR4D	MTA_SR4D_LB_20110309103326	-13.6726	122.0503	6
9/3/11		Dove	SR4D	MTA_SR4D_Apex_RA_20110309104832	-13.6726	122.0503	6
9/3/11		Dove	SR4D	MTA_SR4D_RA_20110309102320	-13.6726	122.0503	6
9/3/11		Dove	SR4D	MTA_SR4D_RB_20110309103113	-13.6726	122.0503	6
9/3/11		Dive Transect	SR4D	AIMS Reef Ecology database	-13.6726	122.0503	6
9/3/11		Coral Collection	SR4S	see Montara Coral Samples database V1.2	-13.6735	122.0507	3
9/3/11		Juvenile Coral	SR4S	Montara Juvenile coral database V1.1	-13.6735	122.0507	3
9/3/11		Dove	SR4S	MTA_SR4S_Apex_LA_20110309093228	-13.6735	122.0507	3
9/3/11		Dove	SR4S	MTA_SR4S_Apex_RA_20110309093018	-13.6735	122.0507	3

9/3/11		Dove	SR4S	MTA_SR4S_LA_20110309090256	-13.6735	122.0507	3
9/3/11		Dove	SR4S	MTA_SR4S_LB_20110309090534	-13.6735	122.0507	3
9/3/11		Dove	SR4S	MTA_SR4S_RA_20110309090029	-13.6735	122.0507	3
9/3/11		Dove	SR4S	MTA_SR4S_RB_20110309090323	-13.6735	122.0507	3
9/3/11		Dive Transect	SR4S	AIMS Reef Ecology database	-13.6735	122.0507	3
10/3/11		Sediment	SR3RC	51A_51B	-13.6368	122.0253	2
10/3/11		Coral Collection	SR4Sth	see Montara Coral Samples database V1.2	-13.6784	122.0542	12
10/3/11		Coral Collection	SR5D	see Montara Coral Samples database V1.2	-13.6988	122.0305	6
10/3/11		Sediment	SR5D	38A_38B	-13.6988	122.0305	6
10/3/11		Juvenile Coral	SR5D	Montara Juvenile coral database V1.1	-13.6988	122.0305	6
10/3/11		Dove	SR5D	MTA_SR5D_Apex_LA_20110310162605	-13.6988	122.0305	6
10/3/11		Dove	SR5D	MTA_SR5D_Apex_RA_20110310162326	-13.6988	122.0305	6
10/3/11		Dove	SR5D	MTA_SR5D_LA_20110310155710	-13.6988	122.0305	6
10/3/11		Dove	SR5D	MTA_SR5D_LB_20110310160023	-13.6988	122.0305	6
10/3/11		Dove	SR5D	MTA_SR5D_RB_20110310155750	-13.6988	122.0305	6
10/3/11		Dove	SR5D	MTA_SR5D_RA_20110310155429	-13.6988	122.0305	6
10/3/11		Dive Transect	SR5D	AIMS Reef Ecology database	-13.6988	122.0305	6
10/3/11		Coral Collection	SR5S	see Montara Coral Samples database V1.2	-13.6986	122.0306	3
10/3/11		Sediment	SR5S	37A_37B	-13.6986	122.0306	3
10/3/11		Juvenile Coral	SR5S	Montara Juvenile coral database V1.1	-13.6986	122.0306	3
10/3/11		Dove	SR5S	MTA_SR5S_Apex_LA_20110310150111	-13.6986	122.0306	3
10/3/11		Dove	SR5S	MTA_SR5S_Apex_RA_20110310145835	-13.6986	122.0306	3
10/3/11		Dove	SR5S	MTA_SR5S_LA_20110310143513	-13.6986	122.0306	3
10/3/11		Dove	SR5S	MTA_SR5S_LB_20110310144258	-13.6986	122.0306	3
10/3/11		Dove	SR5S	MTA_SR5S_RA_20110310143254	-13.6986	122.0306	3
10/3/11		Dove	SR5S	MTA_SR5S_RB_20110310143311	-13.6986	122.0306	3
10/3/11		Dove	SR5S	MTA_SR5S_RC_20110310144035	-13.6986	122.0306	3
10/3/11		Dive Transect	SR5S	AIMS Reef Ecology database	-13.6986	122.0306	3
10/3/11		Sediment	SR6D	40A_40B	-13.6939	121.9950	6
10/3/11		Juvenile Coral	SR6D	Montara Juvenile coral database V1.1	-13.6939	121.9950	6
10/3/11		Dove	SR6D	MTA_SR6D_Apex_LA_20110310100213	-13.6939	121.9950	6
10/3/11		Dove	SR6D	MTA_SR6D_Apex_RA_20110310095950	-13.6939	121.9950	6
10/3/11		Dove	SR6D	MTA_SR6D_LA_20110310093814	-13.6939	121.9950	6
10/3/11		Dove	SR6D	MTA_SR6D_LA_20110310094549	-13.6939	121.9950	6
10/3/11		Dove	SR6D	MTA_SR6D_RA_20110310093555	-13.6939	121.9950	6
10/3/11		Dove	SR6D	MTA_SR6D_RA_20110310094312	-13.6939	121.9950	6
10/3/11		Dive Transect	SR6D	AIMS Reef Ecology database	-13.6939	121.9950	6
10/3/11		Sediment	SR6S	39A_39B	-13.6938	121.9954	3
7/5/11		Dive Transect	A5S	AIMS Reef Ecology database	-12.2642	122.9584	3
7/5/11		Dive Transect	A5D	AIMS Reef Ecology database	-12.2645	122.9580	6
7/5/11		Dive Transect	A6S	AIMS Reef Ecology database	-12.2291	122.9489	3
7/5/11		Dove	A6S	MTA_A6S_20110507	-12.2291	122.9489	3
7/5/11		Dive Transect	A6D	AIMS Reef Ecology database	-12.2291	122.9488	6
7/5/11		Dove	A6D	MTA_A6D_20110507	-12.2291	122.9488	6
8/5/11		Dove	A5D	MTA_A5D_20110508	-12.2645	122.9580	6
8/5/11		Dove	A5S	MTA_A5S_20110508	-12.2642	122.9584	3
9/5/11		Dive Transect	A3S	AIMS Reef Ecology database	-12.2513	123.1553	3
9/5/11		Dive Transect	A3D	AIMS Reef Ecology database	-12.2555	123.1550	6
9/5/11		Dove	A3D	MTA_A3D_20110509	-12.2555	123.1550	6
12/5/11		Dive Transect	SR6S	AIMS Reef Ecology database	-13.6928	121.9942	3

7. Glossary

AIMS	*Australian Institute of Marine Science*
AMSA	*Australian Maritime Safety Authority*
ANOSIM Test	*Analysis of Similarity Test*
ANOVA	*Analysis of Variance*
ANZZEC	*Australian New Zealand Environment and Conservation Council*
ARMCANZ	*Agriculture and Resource Management Council of Australia and New Zealand*
CA	*Approximately*
CCA	*Crustose Coralline Algae*
CI	*Confidence Intervals*
C/N Ratios	*Carbon/Nitrogen ratios*
CSIRO	*Commonwealth Scientific and Industrial Research Organisation*
CUM –	*Cumulative*
DBT	*Dibenzothiophene*
dbRDA	*Distanced Based Redundancy Analysis*
DF (df)	*Degrees of freedom*
DCM	*Dichloromethane*
DISTLM	*Distance Based linear model*
DOV	*Stereo Diver Operated Video*
DSEWPaC	*Department of Sustainability, Environment, Water, Populations, & Communities*
DW	*Dry Weight*
EPA	*Environmental Protection Authority*
ESBTU	*Equilibrium Partitioning Sediment Benchmark Toxicity Units*
FOC	*Fraction Organic Carbon*
GAM	*Generalised Additive Model*
GLM	*Generalised Linear Models*
GBR	*Great Barrier Reef*
GBRMPA	*Great Barrier Reef Marine Park Authority*
GPS	*Global Positioning System*
GCMS	*Gas Chromatography Mass Spectrometry*
HC	*Hydrocarbon*
IMCRA	*Integrated Marine and Coastal Regionalization of Australia*
ISQG	*Interim Sediment Quality Guidelines*
JUV	*Juvenile*
Km	*Kilometres*
Lat	*Latitude*
Long	*Longitude*
LTM	*Long Term Monitoring*
MIX	*Length-Frequency Analysis*
M (m)	*Metres*
MS	*Mean Squares*
MWHP	*Montara Well Head Platform*
NA	*Not Applicable*
N (n)	*Sample size*
NM	*Nanometres*
NAPL	*Non-aqueous Phase Liquid*
nMDS	*Non-metric Multidimensional Scaling Ordination*
NW	*North West*

NWA	*North West Australia*
Obs	*Observations*
OC	*Organic Carbon*
OTP	*Orthoterphenyl*
OSS	*Oceanic Shoals in the meso-scale region of the IMCRA*
P	*Probability Value*
PAHs	*Polycyclic Aromatic Hydrocarbons*
PCO	*Principal Coordinate Analysis*
PERMONOVA	*Permutational Multivariate Analysis of Variance*
PRIMER	*Plymouth Routines in Multivariate Ecological Research*
pg	*Pico gram*
ppm	*parts per million*
R^2	*Coefficient of determination*
RDA	*Redundancy Analysis*
RIC	*Reconstructed Ion Chromatographs*
RV Solander	*Research Vessel Solander*
SE	*Standard Error*
SCUBA	*Self- contained Underwater Breathing Apparatus*
SD	*Standard Deviation*
± SD	*plus or minus Standard Deviation*
± SE	*plus or minus Standard Error*
SIM	*Selected Ion Monitoring*
SIMPER	*Similarity Percentage Analysis*
SQGS	*Sediment Quality Assessment Guidelines*
THC	*Total Hydrocarbons Concentration*
TOC	*Total Organic Carbon*
TL	*Total Length*
Tukey HSD Test	*Tukey's Honest Significant Difference Test*
UCM	*Unresolved Complex Material*
µg	*Micro gram*
µg/g –	*Micro gram per gram*
µL	*Micro litre*
µm	*Micro metre*
US EPA	*United States Environment Protection Authority*
UV	*Ultraviolet*
UVC	*Underwater Visual Census*
UVF	*Ultraviolet Fluorescence Analysis*
VAR	*Variance*
WGS84	*World Geodetic System (Reference coordinate system used by GPS)*