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30 May 2011

Diversity, abundance and distribution of intertidal invertebrate species in the Ningaloo Marine Park

Final Report 30 May 2011
WAMSI Project 3.2.2b

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1. Executive Summary

1.1 Date

30 May 2011

1.2 Project Title & Number

3.2.2b Diversity, abundance and distribution of intertidal invertebrate species in the NMP

1.3 Project Leader

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1.5 Dates Covered

July 2007 to May 2011

1.6 Summary

(for even shorter account see section 2.1)

Aims and approach

A quantitative pilot study of the composition of the benthic community of macro-invertebrates on intertidal rocky platforms was undertaken to (A) provide detailed information on variation in biodiversity along the length of the Ningaloo Marine Park and (B) determine the appropriate design of a monitoring protocol powerful enough to determine predefined levels of change. These general overall aims were in the context of the Ningaloo Marine Park Draft Management Plan of 2004, which set out a vision of maintaining the ecological values in the Park, and protecting it from adverse human impacts.

The design of research and monitoring schemes must include several crucial features: (1) adequate, replicated sampling for each combination of time, location and any other controlled variable; (2) adequate, replicated sampling in areas with and without human impacts; and (3) pre-defined, quantitative criteria for what constitutes an important, continuing temporal trend or concerning difference between the sanctuary zones and impacted areas, or between

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sanctuary zones some time after their establishment and their initial conditions. Even well-designed studies have to overcome the challenges of i) natural variability and patchiness at different temporal and spatial scales, and ii) natural events that overwhelm, obscure, or counteract the effects of human impacts.

The Ningaloo Marine Park Draft Management Plan of 2004 seemed to fail to appreciate, comprehend, or even acknowledge the existence and magnitude of natural spatial and temporal variability against which to judge what is major rather than minor, foreseen rather than accidental loss, or prolonged rather than transient. Of course, defining the size of differences or changes that are critical (the maximum acceptable impact or effect) in any precise quantitative way will be difficult because any general definition cannot apply to all components of an ecological community, at all times, and all places within an area as large as Ningaloo Marine Park. Therefore, cases probably need individual attention in setting appropriate effect sizes indicative of concern. One view is that critical-effect sizes in advance with reference to the local environment, yet the Draft Management Plan was silent about this issue. Specification of effect sizes is most often in the context of power analysis and the importance of both kinds of errors: Type I (rejecting a null hypothesis when it is true), and Type II (accepting a null hypothesis when it is false). Both require specification in studies about potential impacts that use an approach involving formal hypothesis testing, and both are relevant to managers trying to make decisions to minimize harm. However, an alternative approach, parameter estimation with confidence intervals emphasizes that the confidence intervals serve the same function as hypothesis testing and show power automatically. There is no way of avoiding careful evaluation of effect size.

Sites

This project examined the assemblages of macroinvertebrates at 36 sites on rocky intertidal platforms from Mildura Wreck in the north to 3 Mile in the south of Ningaloo Marine Park during 2007 to 2010, visiting 18 sites twice. There were two or more sites in seven of the

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Sanctuary Zones, and one site each in two other Sanctuary Zones, totaling 22 sites. Eleven sites were close to but outside Jurabi, Bateman Bay, Pelican, Gnarraloo Bay, and 3 Mile Sanctuary Zones, and the remaining three, outside sanctuary zones, improved the geographic distribution of the sites (Table 1 - next page). Within the array of sites, and times they were sampled, there are sets of sites that are suitable for making comparisons among geographical regions in the Park, Inside and Outside of Sanctuary Zones and Inside and Outside Sanctuary Zones at different times, and for contrasting spatial with temporal variability. These comparisons are addressed for specific cases in other parts of this summary, and in detail in the research chapters.

Sampling and macroinvertebrates

At each site, our standard sampling scheme involved careful searches of 20 1-m² quadrats in order to count the number of individuals of each species. Overall, the 31059 individuals in the 1744 1-m² quadrats were allocated to 289 species of invertebrates of which most were gastropods (127 species), but included cnidarians (50), echinoderms (33), crustaceans (28), bivalves (19), chitons (12), and unusual taxa (20). Ninety-two or 32% of these species occurred as 1 individual, so additional sampling will continue to discover new species, and it is unlikely that any sampling program will ever be able to extensive enough to reveal all the species living on rocky platforms in the Park. Sites north of Yardie Creek, and sites south of Bateman Bay shared many species, but there were species found in the north only or in the southonly, indicating that future studies wishing to include a complete view of the macroinvertebrates must include sites along the length of the Park. The wider distribution of the 102 species for which we have precise identifications (mostly but not restricted to gastropods) suggests that few species are restricted the Park, and many have distributions that extend to other states.

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Table 1. Sites in relation to sanctuary zones, and nature of protection. Regions (shown in Figure 1) and sites are listed in order from north to south. * indicates sanctuary zones which do not extend to shore, so the sites are not strictly in the sanctuary zone; ** indicates that the shoreline is a “Special Purpose (Shore-based Activities) Zone; *** indicates a site used to study giant clams only. (Table 1 in Research Chapter 1).

Region	Sanctuary Zone	Sites Inside Zone	Location and Sites Outside Zone
B	Lighthouse Bay**	Mildura Wreck Mildura Wreck West Surfers North Surfers South	
	Jurabi**	Jurabi In 1 Jurabi In 2 Jurabi In 4 Jurabi In 3	North of northern boundary: Jurabi Out 2 Jurabi Out 3 Jurabi Out 4 Jurabi Out 1
C	Mangrove Bay	Mangrove Bay Mangrove Point	
D	Mandu	Mandu South Cobble Mandu South Flat	South of southern boundary: Pilgramunna
	Osprey Bay		South of southern boundary: Yardie Creek North Yardie Creek South
E	Bateman	Bateman Bay In	North of northern boundary: Bateman Bay Out 2 Bateman Bay Out 1
	Maud**	Coral Bay North Coral Bay North no map*** Coral Bay South	
	Pelican**	Elle’s In	South of southern boundary: Elle’s Out
F	Gnarraloo Bay*	Gnarraloo Bay In 2 Gnarraloo Bay In 1	Gnarraloo Bay Out 2 Gnarraloo Bay Out 1
	3 Mile*	3 Mile North 3 Mile In 2 3 Mile In 1	South of southern boundary: 3 Mile Out 1 3 Mile Out 2

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Focal species - cowries

Several of our analyses focused on particular species because of their abundance or status as a targeted or iconic species. Two potentially targeted species, the cowries *Cypraea caputserpentis* (serpent-head cowry) and *C. moneta* (money cowry) have wide geographic distribution, and within the Park one or both occurred at 26 sites, but in low abundance, rarely exceeding 1 m⁻². Based on patterns of densities over time at these sites, recruitment and mortality of cowries varied considerably among sites, especially for *C. moneta*, even over the short period of this study. Comparisons of samples of cowries from four sites inside and four sites outside Jurabi Sanctuary Zone in February 2010 had *post hoc* powers to detect a two-fold difference in abundance of cowries inside and outside the zone of 0.113 and 0.399 for the two species (i.e., probability of making a Type II error (concluding there is no difference when there is) 0.887 and 0.601). Expressed in a different way, to achieve a power of 0.80, one of the convention values, these comparisons would need many more replicate sites (43 or 9) than seems possible, either logistically, or from lack of suitable sites.

Cowries during daytime low tides are often hidden, and we tried to determine which microhabitat they preferred. At all the scales of our sampling, from sites within the Ningaloo Marine Park, to individual belt transects and 1-m² quadrats to microhabitats within those, the occurrence of an individual cowry probably depends on more factors than we considered, and it is difficult to specify characteristics of prime habitat that apply to all sites.

Focal species - giant clams

The small giant clam, *Tridacna maxima*, is an iconic, tropical species with its brightly-colored mantle a conspicuous feature of many platforms at Ningaloo Marine Park, where it is unusually abundant. We investigated giant clams as a focal species because they provided a tractable system to investigate some general ecological issues about dynamics of populations. Understanding variability of recruitment and mortality is essential for assessing changes due to perceived disturbances or attempts to conserve populations. In the absence of long-term

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studies, we examined population density and size-frequency distributions of *T. maxima* at 20 sites where the clams are abundant on discontinuous, intertidal rocky platforms attached to the shoreline. Abundance ranged over two orders of magnitude (0.05 - 8 m⁻²), and size ranged from 1.5 to 31.0 cm. The shapes of the size-frequency distributions varied substantially, indicating variability in recruitment and mortality, including failures of cohorts to recruit and catastrophic events of mortality. Consistency of recruitment, as indexed by the coefficient of variation of the size-frequency distribution, was greater toward the north of the park, on intertidal platforms with greater complexity across their widths, and with smoother surfaces in the part of the platform occupied by the clams. The average turnover time was estimated at 5.5 years, giving a median age of 13 years. Variation among sites was large, however, highlighting the importance of variability of the dynamics of local populations, and the need for long-term studies to understand any particular population.

Focal species - abundant macroinvertebrates demonstrate spatial and temporal variability

We selected 15 species for detailed analyses of spatial and temporal variability because they were most abundant overall in our sampling by 1-m² quadrats. Ten were gastropods, three were bivalves, one a coral and one a sea urchin. The coral and small giant clam (*T. maxima*), get some of their energy from endosymbiotic zooxanthellae, as well as from small particles in the water. The bivalves are suspension feeders, depending on particles in the water. The vermetid uses mucus threads to capture particles from the water. The ceriths and the stromb probably feed on small organic particles in sediments. The turban shell, trochid, and sea urchin are herbivores. The thalassid and cone are predators. Thus, this selection of species includes examples of most kinds of feeding by marine organisms. The coral, the bivalves, and the vermetid are permanently attached to the surface of the platform, and the urchin is usually associated with a depression in the surface, while the remaining species can move.

The most important feature of the abundances of these 15 species of macroinvertebrates on rocky intertidal platforms at Ningaloo Marine Park is the pervasive spatial variability. Spatial

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variability at a regional scale was obvious among four sanctuary zones (Jurabi, Bateman Bay, Gnarraloo Bay, and 3 Mile) for three of the seven species analyzed because the variance component exceeded 50% and the Zone term was statistically significant in an analysis of variance. However, the variance component ranged from 15 to 30 % in the other four, thus adding substantial variation over that present within the sites among the quadrats. Large-scale spatial variability was also obvious among sites in general because the magnitude of effect (ω^2 , one measure of effect size) was greatest for Site for 14 of the 15 species when compared with the magnitude of effect for Year and Year x Site, with highest values ranging from 36 - 70 % in six species and lowest values ranging from 15 to 1% in six others. Spatial variability at this scale, therefore, could be large, but was not universal, and depended on the species considered. Spatial variation was very much less between adjacent sites as judged by the small effect size of Status (In or Out of the sanctuary zone, kms apart). However, this would be an expected result if the platforms at adjacent sites were matched in physical attributes, as we attempted to do.

Temporal variability between 2007 and 2009 was very much less than spatial variability. The magnitude of effect associated with Year ranged from 0 to only 5.4%. The two species with the highest values, *Tectus pyramis* and *Turbo hainesi*, were both encountered, mainly in 2007, as small, newly-recruited individuals. Perhaps this temporal variability reflects variation in the abundance of cohorts of recruits that do not survive well on the platforms. The species with no temporal variability were *Echinometra mathaei*, *Conus sponsalis*, and *Morula uva*. The sea urchin is known to have sporadic recruitment and long-lived adults, so this might explain our observations of exclusively adult urchins with little variation between years. The two gastropods belong to groups that can live for several to many years.

Judging temporal variability by the effect sizes (measured as r , which ranges from 0.0 to 1.0) associated with Year in analyses of variance tables provides the same view of temporal variability as the magnitude of effects. The effect sizes in the analyses of the seven species at the eight sites inside and outside sanctuary zones were tiny, the largest only 0.081, and thus explaining only 0.66% of the variation. The effect sizes for these seven species were larger in the analyses of all the sites, ranging from 0.011 to 0.187, but these are still small effects by

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conventional standards. The other eight species had effect sizes of 0.003 to 0.284, the largest approaching a “medium” effect size. For the 15 species the magnitude of effect is highly positively correlated with (effect size)², so these measures provide almost identical views of temporal variability.

These evaluations of spatial and temporal variability suffer from the same difficulty because in almost all the analyses there were statistically important interactions between places and time, meaning that there are extra additive effects of the individual combinations of levels of the factors associated with space and time over and above the main effects of the levels of space and time. However, given the dominating size of the spatial variability in most cases, the influence of the extra variability due to the interaction would be relatively small.

There are some logical reasons why spatial variability far exceeded temporal variability in these data. The first is that the number of sites is so much greater than the two times; there was much more opportunity to find spatial variation. The second, related reason is that the two years are close together, and the processes that produce temporal variation, variations in recruitment and mortality with time, did not have long to act. Related to this is the dependence on life history characteristics of individual species in determining their population dynamics, the frequency and extent of numerical changes. Some species, such as *Echinometra mathaei* and *Tridacna maxima*, are known to be long-lived, so their populations show inertia, changing little from year to year, unless they experience catastrophic conditions. Many gastropods have life-spans of several years, and few species on the platforms would have annual life cycles. One suggestion about judging whether populations are stable over time has been to observe populations long enough that there is a complete turn-over of individuals in it. By this criterion, studies such as ours, or continuing monitoring schemes, probably need to involve 5 to 10 or more years.

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Spatial and temporal variability in multivariate analyses of assemblages of invertebrates

To analyze the composition of the assemblages of macroinvertebrates using multivariate methods for comparisons among sites and among times, we used the sum of each species sampled in the quadrats adjusted to be equivalent to the sum in 20 in the 1-m² quadrats and transformed by $\log_{10}(x+1)$ to reduce the influence of extremely abundant species. We calculated Bray-Curtis similarity matrices for all pairs of sites in several subsets of the data to estimate and compare spatial and temporal variability. We used non-metric multidimensional scaling ordinations (nMDS), and canonical analyses of principal co-ordinates ordinations (CAP) to visualize the relationships among sites, and permutational multivariate analysis of variance for formal statistical tests. The samples involved three years, 2007 (18 sites in north and south), 2008 (10 sites in the north), and 2009 (32 sites in the north and south of the Park).

The composition of the assemblages of varied at all geographic scales that we considered. There were latitudinal differences, but considerable overlap between north and south parts of the Park. Sites in four categories of management (outside sanctuary zones, in sanctuary zones, in Special Purpose Area, and inshore of a sanctuary zone that does not extend to the shoreline) were intermixed in the ordinations, but sites in the south of the Park do not have fully protected intertidal platforms.

The analyses of variance revealed that there were statistically significant interactions between Date (2007 and 2009) and Region (north and south) and Date and Sanctuary (nine zones in the Park). This means that the effect of Date was inconsistent between the two regions, and among the nine zones. For example, the four sites in Lighthouse Bay Sanctuary Zone differed little among each other and between years, while two sites in 3 Mile sanctuary were similar in composition of assemblage of invertebrates within years, but differed drastically between years. Spatial variability was 1.5 or 2.0 times larger than temporal variability. The detection of these statistical interactions between space and time suggest that future sampling of these sites could reveal influences of different management regimes.

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Physical features of intertidal platforms and classification of morphotypes of platforms

One of the overwhelming results of our analyses of assemblages of macroinvertebrates and of individual, focal species was the pervasive spatial variation which of course has serious consequences for detecting differences and measuring changes. Our hope was that by analyzing characteristics of the platforms at the sites that we sampled we could discover some of the features of the environment that were correlated with the assemblages of animals, and therefore provide an explanation for some of the spatial variation in the assemblages. We conducted a pilot study, followed by an extensive analysis of all our sites in 2009, at spatial scales from within the site in quadrats and over ten meters, within the entire platform, and within context of the platform in its landscape.

The pilot study was encouraging because it suggested that the effect of the physical features of the platforms on the assemblages of macroinvertebrates could be great. There was a remarkable positive correlation in how much members of a pair of sites differed in their assemblages of invertebrates and in their environmental features. Two rugosity indices, measuring undulations in the surface of the platform, one at a 2-m scale and the other at 7.4-m scale may play contrasting roles (because their correlations with the axes of an ordination were at an angle). We used the insights from this pilot study to refine what we measured about the environment in a more detailed study.

The analysis of spatial patterns is important for scientists specialising in both geomorphology and ecology to understand variance at different scales. Identifying common processes controlling the morphology of rock platforms and intertidal invertebrate assemblages provides an understanding of the “bigger picture” and an insight into landscape ecology. The aim of this project was to develop a typology of shore platforms within the Ningaloo Marine Park, Western Australia from the investigation of morphological features measured onsite during visits and offsite using charts and maps to determine whether shore platform morphology can help explain and predict an intertidal invertebrate assemblage. Cluster analyses were used to investigate patterns of morphological similarity in all morphological

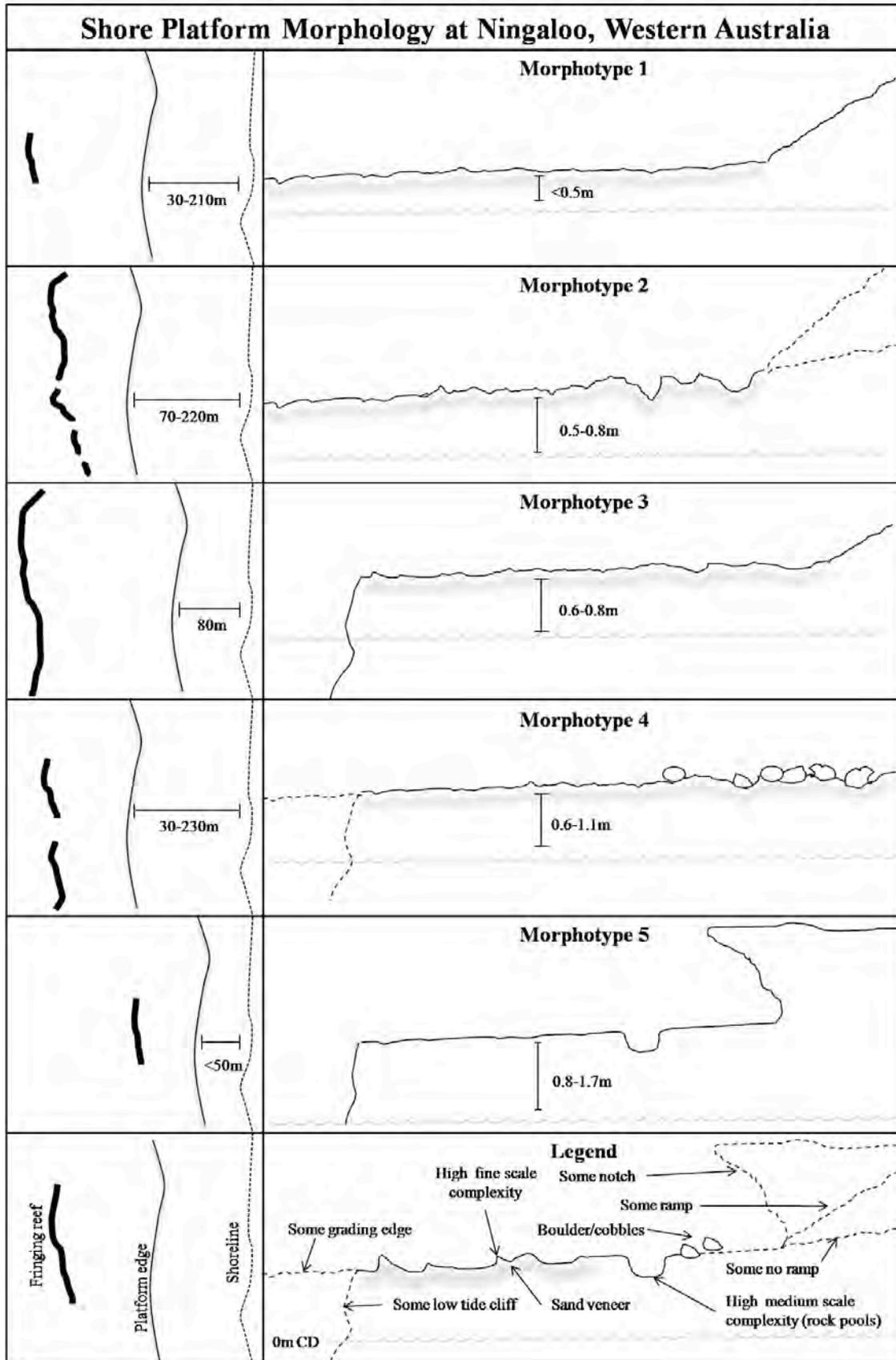
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data and subsets of data to determine the best description of site morphology. The subset of data used to determine morphotypes included 10 variables measured both onsite and offsite and identified 5 morphotypes (Figure - next page). Site morphology differed regionally with the major differences likely due to wave energy and protection by offshore reef. The patterns of dissimilarity of the assemblages of macro-invertebrates at each site from counts in 20 1-m² quadrats were correlated with the patterns of dissimilarity of morphological characters of the site. Furthermore, ordinations of the invertebrate assemblage at each site constrained by the factor morphotype show more defined groupings of sites with the same morphotype. Invertebrate assemblages differed regionally and may be explained by broader scale processes not considered in this project. Predicting the abundance of “key animals” (i.e. *Cypraea* spp. (cowries), *Tridacna* sp. (giant clams), *Conus* spp. (cones), and corals) is difficult using this typology, but the abundance of other species (*Siphonaria* spp. (pulmonate limpets), *Thais orbita* (predatory snail), *Cronia avellana* (scavenging snail), *Strombus mutabilis* (herbivorous snail), and *Septifer bilocularis* (suspension-feeding mussel)) can be predicted with confidence. This evaluation of the morphological types of rocky intertidal platforms will add base knowledge to rocky coast geomorphology in Western Australia and provide coastal managers at Ningaloo with a tool to guide and focus site-specific invertebrate research.

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Trial of monitoring protocols and a comparison inside and outside of a sanctuary zone

Some analyses presented in milestone reports and in research chapters in this final report suggested that four replicate sites might be adequate to detect twofold differences in selected features of the assemblage of invertebrates inside and outside the boundaries of sanctuary zones. In February 2010, we conducted an intensive study to test this idea.

For monitoring programs to be successful they require sampling methods that provide accurate data, are cost-effective and repeatable over time. This study tested the application of three sampling methods (systematic grid quadrats, random quadrats and timed search) for use in monitoring macroinvertebrates on intertidal rock platforms in the Jurabi Sanctuary Zone of the Ningaloo Marine Park. Monitoring is required to assess the effectiveness of the sanctuary zones in protecting the invertebrates inhabiting the Ningaloo Marine Park. Eight sites spanning 1.59 kilometres on intertidal platforms were chosen for the study. Four sites lay inside the sanctuary zone (In) and four outside (Out) to allow comparison of the two areas. There was no significant effect of geographical position on the assemblage data. We detected more species and individuals inside the sanctuary zone than outside with the timed search finding significantly more species than both other methods. The assemblages differed inside and outside the sanctuary zone. This effect was detected by the grid and random methods using replicate 1-m² quadrats. The assemblage data collected by the grid and random methods did not differ, possibly due to similarities in the number of replicates used and the area covered. The minimum sampling effort required to detect a difference between sites inside and outside of the sanctuary zone was 15 quadrats for both grid and random methods at a minimum of 8 sites. Data collected from 2007 to 2010 found no difference between sites inside and outside of the sanctuary zone. However, this result may be unreliable due to fewer sites being sampled in previous years.

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2. Key findings and Recommendations

2.1 Objectives and Outcomes - Key Findings

WAMSI Project Plan Node 3 Project 2, Subproject 2 had three important questions that were relevant to our work on the intertidal rocky platforms, which came under the name and code “Intertidal Invertebrate Surveys 3.2.2 b”:

- “1. What is the species diversity of key flora and fauna in selected representative habitats
2. What is the abundance, size composition and distribution of these key species
4. How do the current abundances of targeted and non-targeted species (subtidal and intertidal) compare with the natural abundances of these species in NMP”

The simple answer to these three questions is that for rocky intertidal platforms our study has produced a list of macroinvertebrates at 36 sites within the Park, with quantitative estimates of their distribution and abundance. We measured the size composition of just one species, the small giant clam, *Tridacna maxima*. As far as we know, our study is the first one to estimate abundances at so many sites within the Park, so these are the first estimates of “natural abundances”. The specific features of our study can be summarized in the following nine points.

1. This study provides a start to an inventory of invertebrates on intertidal platforms at Ningaloo Marine Park, and some insights for the design of sampling schemes to detect differences among places and changes over time.
2. We used careful searches of replicate 1-m² quadrats to quantify macroinvertebrates living at 36 sites from Mildura Wreck in the north to 3 Mile in the south of the Park, including sites in Sanctuary Zones, in Special Purpose Areas, onshore from offshore Sanctuary Zones, and in Recreational Zones.
3. Of 289 species found in our samples, only 3 species may be restricted to Ningaloo Reef, 127 species were gastropods, and 92 species were represented by single individuals. All of

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the carefully identified species with known distributions also occur outside the Park, many extending to other states.

4. Cowries (*Cypraea cauputserpentis* and *C. moneta*) provided a case study for detecting differences outside and inside Jurabi Sanctuary Zone. Their overall scarceness and variable abundance meant that detecting a twofold difference between inside and outside the zone, even with 4 replicate sites in each condition, would have very low statistical power, or require impossibly large number of replicate sites.

5. Understanding variability of recruitment and mortality is essential for assessing changes due to perceived disturbances or attempts to conserve populations. An intensive study of small giant clams, *Tridacna maxima*, at 20 sites substituted space for time in the absence of long-term studies. Our interpretations indicated variability in recruitment and mortality, including failures of cohorts to recruit and catastrophic events of mortality. Consistency of recruitment was greater toward the north of the Park, on intertidal platforms with greater complexity across their widths, and with smoother surfaces in the part of the platform occupied by the clams. Our calculations suggested that the clams had a median age of 13 years.

6. In samples from 2007 and 2009, analyses of 15 of the most abundant species, representing most kinds of feeding by marine invertebrates, indicated that spatial variation was pervasive and overwhelmed temporal variation, as might be expected over the short time interval, and from species being long-lived. Spatial variation at the scales of our study (among geographical regions, among sites within regions, among quadrats within sites) could be very large, but was not universal, and depended on the species considered.

7. Spatial and temporal variability in the composition of the assemblages of invertebrates was similar to that of the individual species; spatial variability predominated over temporal variation, and demonstrated that the assemblages had different membership according to the region of the Park. Sites in Sanctuary Zones, in Special Purpose Areas, onshore from offshore Sanctuary Zones, and in Recreation Zones showed broad overlap in ordinations of

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the assemblages, indicating that the sites in Sanctuary Zones represent much of the variation in composition of the macroinvertebrates on rocky platforms.

8. Part of the spatial variation in assemblages and individual species appeared to be related to particular features of the physical environment within m² areas, the whole site, the whole platform, and the larger setting of the platforms. Correcting for these features statistically may allow refined measures of differences and changes. These physical features and others helped organize the variety of platforms into five morphotypes that may help in selection of sites for future studies, and explain features of the distribution of particular species.

9. In a test of some predictions from power analyses, we used four sites inside Jurabi Sanctuary Zone and four sites outside to determine whether we could detect an effect of Sanctuary Zone. The assemblages of invertebrates differed inside and outside of the zone, and simulations suggested that although the eight sites were necessary to retain that differentiation, the number of quadrats per site could be reduced.

2.2 Implications for Management - Recommendations

i. Managers must understand the extent and nature of natural variation in abundances of intertidal organisms at different places at the same time and the same place at different times. Our data show individual species varying from none to lots, from place to place within the Park, and from some to not detectably between 2007 and 2010.

ii. Against this background of spatial and temporal variation, desired trends for “diversity” and “biomass” to be “constant or positive” are clearly ambitious. Managers must distinguish between changes that are major rather than minor, foreseen rather than accidental, and prolonged rather than transient.

iii. If continued monitoring programs are implemented, they should be planned carefully, with consideration of Type I and Type II errors, defined effect sizes (alternatives to null

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hypotheses), and in the light of the (large) size of residual variation that pilot studies such as this project suggest will apply. The appropriate unit of independent replication should be a “site” (as used in this project), and the prognosis from our power analyses is that, even for several fold effect sizes, the number of replicate sites per treatment should be several.

iv. Additional sampling of intertidal invertebrates will reveal species not detected by this study. This is a natural, expected consequence of the underlying nature of assemblages of invertebrates. Many species are rare; most species occur at low densities.

v. Long-term studies spanning 5 to 10 years or more will be required to reveal the dynamics of local populations of long-lived intertidal invertebrates such as *Tricacna maxima* and *Echinometra mathaei*. Some species will be ephemeral.

vi. Because of the regional differences in species composition of assemblages of intertidal invertebrates, continued monitoring schemes must include sites along the length of Ningaloo Marine Park.

2.3 Other Benefits

2.3.1 Tools, Technologies and Information for Improved Ecosystem Management

i. Our plan to produce an illustrated field guide to the macroinvertebrates of the rocky intertidal platforms has been delayed until some time after May 2011.

ii. We will contribute metadata and data of our quadrat sampling which will provide quantitative estimates of 289 species in macroinvertebrates at 36 sites within Ningaloo Marine Park. These will be useful for comparison with future quantitative estimates.

iii. For 33 of these sites we will also contribute metadata and data describing the physical characteristics of the areas sampled for macroinvertebrates, the platform where the site was

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located, and its larger setting in the environment. These data were used to group the intertidal platforms into five morphotypes.

2.3.2 Forecasting for Natural Resource Management Decisions

- i.** The main conclusion from our study of intertidal platforms in Ningaloo Marine Park is that spatial variation in the composition of the assemblage of the macroinvertebrates is so large that little could be predicted. Temporal variation can be unexpectedly large.
- ii.** The prognosis from our power analyses is that detecting differences between sites under different management regimes will be difficult, as will be detecting changes over time. The essential, and as yet missing, decision by managers is what effect size is important enough to elicit remedial action.

2.3.3 Impacts

- i.** Our project has not been involved in “the knowledge transfer matrix process”

2.4 Problems Encountered (if any)

One general problem in any environmental study is the trade off between inclusive spatial coverage and adequate local sampling. Our challenges were to cover the whole Ningaloo Marine Park, to have replicate sites for all the conditions of interest (Sanctuary Zones, Special Purpose Areas, Recreation Areas, and areas with offshore Sanctuary Zones), and to sample each site quantitatively, and comprehensively. The final report indicates the extent of our success. The basic issue is constraint imposed by funds, and personnel.

Diversity, abundance and distribution of intertidal invertebrate species in the Ningaloo Marine Park

Chapter 1: Diversity, abundance and distribution of intertidal invertebrate species in the Ningaloo Marine Park - general approach (25 pages)

Chapter 2: Species living on the rocky intertidal platforms in Ningaloo Marine Park (30 pages)

Chapter 3: Cowries on rocky intertidal platforms at Ningaloo Marine Park (35 pages)

Chapter 4: Evidence of large, local variations in recruitment and mortality in the small giant clam, *Tridacna maxima* (Röding, 1798), at Ningaloo Marine Park, Western Australia (31 pages)

Chapter 5: Spatial and temporal variability in abundance of 15 selected species of invertebrates at 18 sites in Ningaloo Marine Park, 2007 and 2009. (21 pages)

Chapter 6: Spatial and temporal variability in assemblages of intertidal invertebrate species in the Ningaloo Marine Park, 2007-2009 (17 pages)

Chapter 7: Do environmental variables explain differences in macroinvertebrate assemblages between intertidal rocky platforms?: a pilot study (11 pages)

Chapter 8: Linkages between intertidal invertebrate assemblages and shore platform morphology in the Ningaloo Marine Park, Western Australia. (116 pages)

Chapter 9: Comparative methods for the monitoring of sanctuary zones on rocky intertidal platforms at Ningaloo Marine Park (68 pages)



Jurabi In 1 - photo by Anne Brearley



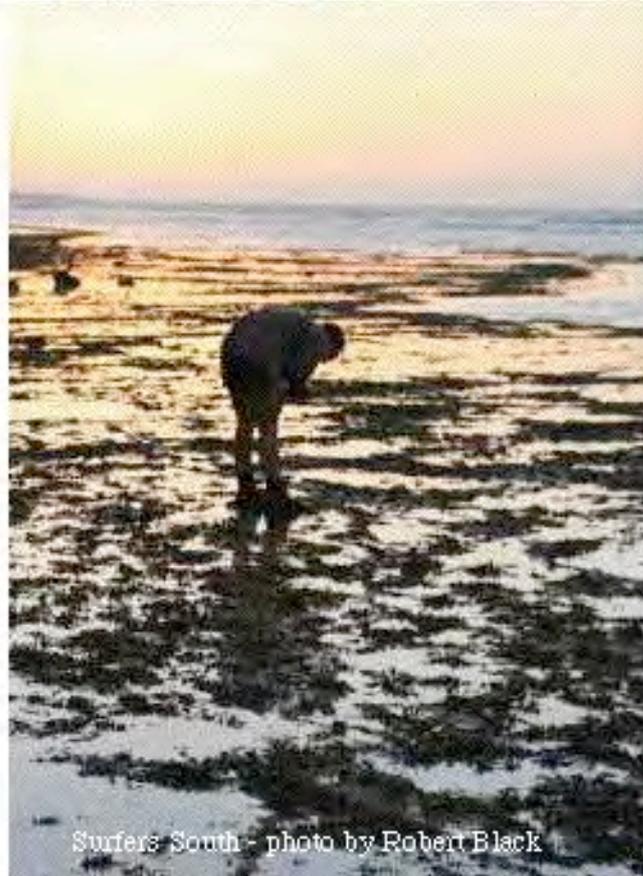
Surfers South - photo by Anne Brearley



Bateman Bay Out 1 - photo by Anne Brearley



3 Mile In 1 - photo by Anne Brearley



Surfers South - photo by Robert Black

**Chapter 1: Diversity, abundance and
distribution of intertidal invertebrate
species in the Ningaloo Marine Park -
general approach**



**Top row: Robert Black, Anne Brearley,
Bottom row: Michael Johnson, Jane Prince**

Introduction: Developing and designing monitoring protocols for benthic habitats at Ningaloo Reef: a pilot study on intertidal rocky shores

We proposed that a quantitative pilot study of the composition of the benthic community of macro-invertebrates of intertidal rocky platforms should be undertaken to (A) provide detailed information on variation in biodiversity along the length of the Ningaloo Marine park and (B) determine the appropriate design of a monitoring protocol powerful enough to determine predefined levels of change. These general overall aims were in the context of Ningaloo Marine Park Draft Management Plan (Anon. 2004) which set out a vision of maintaining the ecological values in the Park, and protecting it from adverse human impacts.

The Ningaloo Marine Park Draft Management Plan (Anon. 2004) outlined an ambitious goal that development and visitors in the next ten years would leave for a variety of habitats and properties of the Ningaloo Marine Park unchanged or better. The management plan dealt specifically with “Shoreline intertidal reef communities” in section 7.1.6 (pp. 32-33). The management objectives were concerned that the “diversity and abundance of shoreline intertidal reef communities” were “not significantly impacted by trampling and recreational collecting.” Of the six strategies, our proposed research addressed two:

“5. Monitor shoreline intertidal reef communities in areas of most risk of degradation from trampling and recreational collecting....”

“6. Undertake research programs to characterize flora and fauna on representative shoreline reef communities with the reserves....”

The performance measures were that the desired trends for “diversity” and “biomass” be “constant or positive”. The management plan also had two long-term targets:

1. No loss of shoreline intertidal reef diversity as a result of human activity in the Park.
 2. No loss of living shoreline intertidal reef biomass as a result of human activity in the Park.”
- The footnote for 2 elaborated about loss with these words: “In this context a loss or change in ”*abundance*” or “*biomass*” excludes losses of a minor or transient or accidental nature.”

These strategies and performance measures are laudable, but seem to fail to appreciate, comprehend, or even acknowledge the existence and magnitude of natural spatial and temporal variability against which to judge what is major rather than minor, foreseen rather than accidental loss, or prolonged rather than transient. Of course, defining the size of differences or changes that are critical (the maximum acceptable impact or effect) in any precise quantitative way will be difficult because any general definition cannot apply to all components of an ecological community at all times and all places within an area as large as Ningaloo Marine Park. Therefore, cases probably need individual attention in setting appropriate effect sizes indicative of concern. Mapstone (1996) views the stipulation of the critical effect sizes in advance with reference to the local environment as having the highest priority, yet the Draft Management Plan was silent on this issue. Mapstone's context was that of power analysis and the importance of both kinds of errors: Type I (rejecting a null hypothesis when it is true), and Type II (accepting a null hypothesis when it is false). Both require specification in studies about potential impacts that use an approach involving formal hypothesis testing. However, an alternative approach, parameter estimation with confidence intervals, championed by Stewart-Oaten (1996), emphasizes that the confidence intervals "directly assess the main concern (effect size), are easy to understand, and display "power" automatically..." (p. 24). There is no way of avoiding careful evaluation of effect size.

Within the context of the Ningaloo Marine Park Draft Management Plan, the WAMSI Project Plan Node 3 Project 2, Subproject 2 had several important questions which were relevant to our work on the intertidal rocky platforms that came under the name and code "Intertidal Invertebrate Surveys 3.2.2 b" (p. 5):

1. What is the species diversity of key flora and fauna in selected representative habitats
2. What is the abundance, size composition and distribution of these key species
-
4. How do the current abundances of targeted and non-targeted species (subtidal and intertidal) compare with the natural abundances of these species in NMP"

It also elaborated several outputs related to the intertidal zone (p. 5):

" Out put 2. Measures of the effectiveness of previously established sanctuary zones for

protecting exploited intertidal invertebrate populations (data reports, scientific papers, inputs to models)

....

Output 6. Baselines for future assessment of the importance of zone size, age, configuration, location on effectiveness for protecting biodiversity (data, data reports) in subtidal and intertidal communities

Output 7. Recommendations on species and methods to be monitored to assess management effectiveness (monitoring protocols, management indicators) for intertidal and subtidal communities”

Intertidal rocky shores were the target for this pilot study because they are one of the marine habitats a) most accessible to visitors, and b) most likely to receive pollutants from the land. Furthermore, because of the simple logistics required for intertidal studies, they are c) the most cost-effective way of initiating the monitoring component of the management plan and d) the protocols established would form a basis for ongoing monitoring in intertidal rocky shores and designing schemes for other habitats.

The design of research and monitoring schemes must include several crucial features: (1) adequate, replicated sampling for each combination of time, location and any other controlled variable; (2) adequate, replicated sampling in areas with and without human impacts; and (3) pre-defined, quantitative criteria for what constitutes an important, continuing temporal trend or concerning difference between the sanctuary zones and impacted areas, or between sanctuary zones some time after their establishment and their initial conditions. One of the best accounts about the design of research about impacts and adequate sampling design remains Roger Green's (1979) book because of its emphasis on general principles of experimental design and statistical analysis that are central to points 1) to 3) above. Even well-designed studies have to overcome the challenges of i) natural variability and patchiness at different temporal and spatial scales, and ii) natural events that overwhelm, obscure, or counteract the effects of human impacts.

Materials and Methods

Design of surveys - spatial component

Our intention was to sample rocky intertidal platforms attached to shore in as many sanctuary zones as was practical. We also wanted to sample adjacent platforms in areas that were outside the sanctuary zones that they would be subject to the same or closely similar environmental conditions and physical features. This proved to be difficult, and our aim was only partially achieved. We were able to find suitable platforms in the five of the six major geographical regions of the Ningaloo Marine Park accessible from the mainland (Figure 1).

Design of surveys - temporal component

We conducted sampling of the fauna on intertidal platforms in August 2007 (18 sites), November 2008 (8 sites, 3 of which were not sampled in 2007), July and September 2009 (32 sites, including 9 sites not sampled previously, improving the geographical coverage), and in an especially focused study in February 2010 (8 sites, including three not sampled previously) (Table 1). Additional details and images of the sites are in Chapter 1 Appendix.

Conditions for sampling

At each of the platforms, we established a site, the center of which is given by the latitude and longitude values in Table 1. The site was in the central part of the platform, avoiding both the seaward edge of the platform and its inshore margin. The site was rectangular, approximately 50 m parallel to shore and 15 m perpendicular to shore, although in August 2007 during preliminary sampling some sites were larger (Figure 2). We chose platforms that were accessible and drained of overlying water at low spring tides predicted to be 0.5 m or lower. Good series of low spring tides on several consecutive days, sometimes two a day, occur in August through October at Ningaloo Marine Park, although suitable tides on fewer days occur in most months. Predicted tides of 0.5 m during daylight allow about 4 hours of

suitable working conditions, during which we could sometimes work at more than one platform. When water covered the platforms during rising and falling tidal conditions, we used glass-bottomed buckets in water up to about 50 cm deep, extending the time we could work effectively.

Quantitative sampling

Our aim was to sample the entire community of macroinvertebrates that lived on the intertidal platforms to achieve our goal of describing the fauna and its distribution on the platforms within the marine park, rather than arbitrarily focusing on particular species. “Macro-” meant what the investigators could easily see or, equally important, feel during searches. Practically, the smallest organisms were about 3 mm in largest dimension. Most of the animals on the platforms were small, 3 mm to 3 cm, although there were many notable exceptions. In consequence of the macroinvertebrates being small, cryptic, and often lodged in crevices, buried in sediment, or obscured under algae or seagrass, our main method of obtaining quantitative samples of the community of organisms had to be intensive searches of relatively small areas. We chose to sample replicate 1-m² quadrats at each site, and aside from some sites in August 2007 and February 2010, we sampled all the organisms in 20 of these quadrats. Our procedure involved haphazardly locating the position of the 20 quadrats within the boundaries of our site, taking care to position the quadrat without reference to what was within the quadrat by throwing a 0.25-m² quadrat ahead of us, and having consistent rules about the orientation of three other 0.25-m² quadrats adjacent to the thrown one. The four 0.25-m² quadrats helped ensure that the entire area was searched uniformly and with equal effort.

In 2007 and 2008 at some sites we sampled more than 20 1-m² quadrats because we wanted to understand the exact nature of the assemblage obtained by the standard number.

In 2007 and 2008 we also sampled at some of the sites using 30 m x 1 m belt transects, with two persons counting conspicuous, larger animals such as echinoderms, giant clams, and

corals within 0.5 m of each side of the transect. We abandoned this method when we realized that even the large, conspicuous animals were not abundant in these samples, and that there were so many more small, crypt organism present that required careful searches that the 1-m² quadrats demonstrated.

Morphology of the intertidal platforms

The assemblages of macroinvertebrates in our samples were very different from site to site, and we suspected that some physical features of the sites might be associated with some of the variation in the assemblages. We measured sets of features at different spatial scales. Features within quadrats, within the area of the sites, and within the platform where the site was were measured during visits to the sites. Features within the larger setting of the platform were measured from charts and maps. This component of our project progressed from a pilot study in February 2009 to a comprehensive study of all 32 sites in July and September 2009. The methods are given in detail in Chapters 3 and 8.

Intensive studies of particular species

Cowries (*Cypraea* spp.), attractive to beachcombers and shell collectors, are candidates for impacts associated with intensive use of intertidal habitats. Therefore, we conducted an intensive study of cowries in February and July 2009 to augment the information that the standard sampling of sites by the 1-m² quadrats. The methods associated with the use of micorhabitats by cowries are explained in detail in Chapter 4.

A second iconic species living on the intertidal platforms is the small giant clam, *Tridacna maxima*. These are conspicuous of the size, brightly-colored, exposed mantle tissue, and relatively high density where they do occur. In August and September 2010, we followed an approach by Ebert and Russell (1988) which required analyses of the size-frequency distributions of samples from many sites, in order to make inferences about dynamics of the

populations. We measured and mapped *T. maxima* at 20 sites as explained in detail in Chapter 5.

Results

Contrasts between inside and outside sanctuary zones

We sampled replicate sites within seven sanctuary zones, and single sites in two more zones (Table 2). For Jurabi, Gnarraloo Bay, and 3 Mile Sanctuary Zones, we were able to sample replicate platforms outside the zones too, thus achieving a balanced design for those zones. For Bateman Bay and Pelican Sanctuary Zones, the design was unbalanced, with only one platform inside Bateman Bay and two outside, and one inside and one outside at Pelican (Table 1). The sites associated with a sanctuary zone or not have “In” and “Out” attached to their names (Table 2); these sites should provide useful contrasts between the two levels of management.

Contrasts within a sanctuary zone

The four platforms in the Lighthouse Bay Sanctuary varied in distance from the main parking lot at Mildura Wreck where many visitors to the intertidal come. Although the four platforms were all in a sanctuary zone, our guess was that the impact of visitors is greatest at Mildura Wreck, followed by Surfers South, next to another parking lot, and least at Surfers North and Mildura Wreck West, which were some distance from the nearest easy access point on the shore. Thus, the Lighthouse Bay sites provide a contrast within a sanctuary zone in intensity of use by beachcombers.

Geographical coverage

There are sets of replicate sites within three other sanctuary zones. We selected two nearby rocky intertidal platforms within the Mangrove Bay Sanctuary Zone because of the special biological features of the location with its mangroves, tidal creeks, protected bay, and sand and mudflats in addition to the rocky platforms. The two platforms at Mandu Sanctuary Zone differ greatly from each other because the habitat of Mandu South Cobble site not a platform like the others but a boulder field at the mouth of a creek. Thus, we expected that this site might differ from others. In Maud Sanctuary Zone, the two sites were immediately north and south of the jetty and launching ramp at Coral Bay, under construction in 2007 when we established the sites.

Three platforms, outside sanctuary zones were included to improve our geographical coverage, and to include additional variants of rocky platforms. Pilgramunna is south of the Mandu South Flat site, and at a stretch could be matched to it as an “Out” site. The two sites at Yardie Creek are on an unusually long, wide platform high in the intertidal. There is a gap between these sites and the next sites to the south in Bateman Bay.

Dependent variables

Our estimate of the benthic community at a site was the assemblage of animals in the sum of all individuals in the 20 1-m² quadrats, providing estimates of absolute and relative abundances of each species, or just their presence and absence for use in multivariate analyses of the assemblages. Aggregation of the information from all 20 quadrats could also be used to estimate various univariate summaries about the assemblage, such as species richness (number of species), number of species standardized to a particular number of individuals or number of quadrats, evenness of distribution of individuals among species, indices of diversity, and total number of individuals. The summation of the abundance, or average, in the 20 1-m² quadrats of any individual species of interest also provides a dependent variable associated with the site. Since these dependent variables provide single

values for each site, the importance of having replicate sites for factors such as Sanctuary Zone or management protocol is obvious.

However, the abundance of any particular species, or group of species, in each 1-m² quadrat also provides valuable information about variation within sites, and the quadrat-specific information forms the lowest level in the hierarchy of our sampling design. For example, when we asked the question (Chapter 4), Does the abundance of money cowries differ on platforms (= sites) inside and outside of Jurabi Sanctuary Zone at its northern boundary?, our design had the following structure. The factor of greatest interest for the northern boundary of the Jurabi Sanctuary Zone was the condition of Sanctuary, either In or Out, and because for our question there were only two possible levels, Sanctuary is a fixed factor, meaning that we were only and especially interested in In and Out. The units in our design that provided independent replication of the conditions In and Out were the Sites.

By February 2010 we had four sites associated with In and four sites with Out (Tables 1 and 2). Because our sampling scheme developed over time, and we added more sites to the original two at Jurabi as time passed, our view is that the sites are random selections of the available sites that met our criteria on each side of the boundary of the sanctuary. Thus, the Sites are a random factor and are nested within the levels of Sanctuary. “Nesting” refers to the fact that each site is unique, and that in our labeling of the sites as In 1 and Out 1, for example, “1” has no implication about the logical relation between those two Sites, which could have been Sites 1 through 8 to recognize their nature. Importantly, the Sites provide the estimate of within-group variation that statistical tests compare to between-group variation to detect differences between groups, if they exist. Therefore, it is the numbers of replicate Sites that this kind of design depends on for appropriate tests of differences between levels of Sanctuary.

The 20 quadrats at each Site are nested within each Site, but because they share the commonality of being associated with the same Site, they cannot be considered independent experimental units with respect to Sanctuary, but they are independent units with respect to

Site. What they contribute to the design is a more precise estimate of the average number of cowries at their site, and an estimate of variation within sites.

This design has consequences for the analyses of the data. For example, to continue the illustration about cowries, the statistical test for the univariate dependent variable of number of cowries per 1-m², would be a nested analysis of variance explained by a table like the following:

Term number	Source of variation	Degrees of freedom	Mean square	F ratio	Critical F $\alpha=0.05$
1	Sanctuary	$(2-1) = 1$	MS_{Sanc}	$MS_{Sanc} / MS_{Site[Sanc]}$	5.99, df=1,6
2	Sites[Sanctuary]	$2 \times (4-1) = 6$	$MS_{Site[Sanc]}$	$MS_{Site[Sanc]} / MS_{Quad[Site, Sanc]}$	2.16 df=6,152
3	Quadrats[Site, Sanctuary]	$2 \times 4 \times (20-1) = 152$	$MS_{Quad[Site, Sanc]}$		
4	Total	$(2 \times 4 \times 20) - 1 = 159$			

Thus, the analysis of variance divides the source of total variation and the degrees of freedom, associated with the 159 df that come from the 160 observations from 20 quadrats in each of eight sites (Term 4 in table), into parts associated with i) differences between two groups (Term 1, between levels of Sanctuary), ii) differences within groups (Term 2, Sites nested within levels of Sanctuary), and iii) differences among the units nested within groups, (Term 3, Quadrats nested within each Site within each level of Sanctuary). The statistical tests are the F ratios formed from the mean squares (= variances), and the table shows how much larger the numerator of the F ratio must be than the denominator to exceed the critical value of F. The critical values of F decline with an increase in the df associated with the denominator of the F ratio, so having more Sites would have decreased the critical value of F for Term 1.

This hierarchical feature of our sampling design, and any like it, obviously involves trade-offs in the context of constraints imposed by effort, time and cost. The answer to a question about differences between levels of Sanctuary (In or Out) depends on the number of replicate Sites within levels of Sanctuary, but a precise estimate of the assemblage, and abundance of any particular species, depends on the size and number of the sampling unit nested within

Sites. Having more sites better answers questions about categories of sites, so one approach, keeping total numbers of quadrats constant, might have been to sample fewer than 20 quadrats at more sites. However, having more and or larger quadrats would give better answers about the composition of the community and the abundance of each species at each site. Table 2 shows our tradeoffs in terms of numbers of sites that could be sampled with 20 1-m² quadrats given our logistics.

A simulation called rarefaction uses the original information on the assemblage in each 1-m² quadrat to estimate, on average, how many species would occur in fewer quadrats than were actually sampled. Thus, for three sites at which we sampled more than 20 quadrats, Figure 2 shows how many species should have been in fewer quadrats. Several features help evaluate our standard protocol of sampling 20 quadrats. First, the steepest part of the accumulation curves occurs well before 20 quadrats at all three sites. Second, all three curves continue to rise after 20 quadrats on the x-axis, indicating that additional species were yet to be discovered. Third, because the curves have not flattened out at their right-hand ends, even 40 or 50 quadrats were not enough to reveal all the species. This is a common, unavoidable aspect of sampling assemblages of species; most sampling schemes cannot be exhaustive enough to find all the rare species. However, 20 quadrat samples would have revealed basic differences in the species richness of the assemblages at these three sites, because the fundamental pattern of the differences in number of species among the sites remains clear for the expected numbers at 20 quadrats. Surfers South with 24 species in 40 quadrats had fewer species expected in 20 quadrats (19), than the 33 expected at Jurabi In 1 with its observed 48 species in 50 quadrats (or its expected 44 species in 40 quadrats), or the 36 expected at Mangrove Bay with its 43 species in 40 quadrats. This feature, combined with the tradeoffs between number of sites sampled, and the number of quadrats per site provides the rationale for our decision to use 20 1-m² quadrats as our standard method of sampling the assemblages of invertebrates on intertidal platforms.

Temporal variation

There is useful structure in the sampling of platforms in 2007, 2008, and 2009 because there were several sets of sites that allow formal, balanced tests of temporal variation. In the north part of the Park, five sites were sampled in all three years (Mildura Wreck, Surfers South, Jurabi Out 1, Jurabi In 1, and Mangrove Bay). We sampled a second set of sites, spread throughout the Park, in 2007 and 2009. These include all sites in the previous list and the rest of the sites sampled in 2007 making 17 in all (Table 2). Furthermore, within these 17 sites, there are four pairs of sites inside and outside sanctuary zones (Jurabi, Bateman Bay, Gnarraloo Bay, and 3 Mile).

In analyzing the temporal aspect of these data sets, the first and important issue is whether the Date of sampling is treated as a fixed or random factor. The crux is whether the investigator or manager is especially interested in August 2007, November 2008, and July/September 2009 (then Date would be a fixed factor), or in three sampling times that are a selection of many possible times (then Date would be a random factor). The decision about this is important because it determines both the way the data are interpreted, and the nature of the statistical analyses. One view is that Date is a random factor because our interest was not in the communities of macroinvertebrates 2007 and 2009, but in the communities at different times so that we could estimate temporal variability in general.

Of course, the same issue is relevant to the other factors in the design, as discussed previously for the Sites at Jurabi Sanctuary Zone where we considered them as random factors, because they were replicates of the conditions of being In or Out of the sanctuary zone. Thus, for the set of sites associated with the four sanctuary zones with pairs of sites inside and outside, the factor Sanctuary with levels In and Out has to be a fixed factor. Also, the particular Zone can be viewed as a random factor because of two aspects. First, unlike the Jurabi example, there are no replicate sites within any of the Zones, so the set fails in the aspect of having replication of the levels of factors of special concern. Second, if we ask the question “Do platforms in sanctuary zones have a larger number of species of macroinvertebrates than adjacent platforms outside sanctuary zones?”, Zone is like a

blocking factor in which each Zone has one example of each level of Sanctuary (In and Out) combined with each level of Date (2007 and 2009), giving 16 observations of number of species in 20 1-m² quadrats. In the jargon of experimental design this is complete block design because we need to take into account the matching of the pairs of In and Out sites, as well as the matching values for Date for each site. The four treatment combinations of Sanctuary x Date occur in each Zone or block. An analysis of variance table for this design would look like this (a random factor in an interaction makes the term random):

Term	Source	df	term whose MS forms denominator in the F test
1 random	Zone	4-1=3	5
	Treatment combination	[(2x2)-1=3]	
2 fixed	Sanctuary	2-1=1	4
3 random	Date	2-1-1	4
4 random	Sanctuary x Date	1x1=1	5
5 random	Zone x Treatment combination	3x3=9	
	Total	(4x2x2)-1 = 15	

This design fails to give powerful tests for the factors Sanctuary and Date because the mean square of the Sanctuary x Date term with 1 df forms the denominator in the tests, and the critical value of $F_{0.05, 1, 15} = 161.4$. However, the test for the Sanctuary x Date term had many more df for the denominator variance so its critical value of F is much smaller ($F_{0.05, 1, 9} = 5.12$). In fact, it is the interaction term that may be of most interest to managers because if the sanctuary zones were enhancing the numbers of species as time passes, relative to outside the zones, this should show up as a significant interaction between Sanctuary and Date. Of course, one way to give this design better ability to test for the Sanctuary factor is to have more levels of Date (i.e., more sampling times), increasing the df associated with Sanctuary x Date. Another feature of this design is that it would provide estimates of the variance components of the random terms, and thus we could judge the relative size of the variation associated with Zone and Date, providing a perspective on spatial and temporal variability, and with and Sanctuary x Date which should be relatively large if sanctuary zones were improving species richness as time passed. The set of five sites sampled on three dates, and the set of 17 sites sampled on two dates are useful in this respect.

Of course, the dilemma about low power for the factor Sanctuary discussed above could have been partially avoided if the original view about Date being a random factor was not so, but rather that Date was a fixed factor because the concern was about 2007 and 2009 as specific times. The analysis of variance table is altered to:

Term	Source	df	term whose MS forms denominator in the F test
1 random	Zone	4-1=3	5
	Treatment combination	[(2x2)-1=3]	
2 fixed	Sanctuary	2-1=1	5
3 fixed	Date	2-1-1	5
4 fixed	Sanctuary x Date	1x1=1	5
5 random	Zone x Treatment combination	3x3=9	
	Total	(4x2x2)-1 = 15	

Now, the statistical tests for the factors Sanctuary and Date and their interaction all use the mean square of term 5 as the denominator for the F tests, so the critical value of $F_{0.05, 1, 9, df} = 5.12$ applies to Sanctuary, but the context of the results of this analysis is about 2007 and 2009 in particular, instead of about dates in general if Date had been a random factor.

The important process for investigators and managers is to plan experiments and monitoring schemes carefully, considering all the factors in the design in the light of the tradeoff between generality and specificity, and evaluating the resulting consequences to the analyses of the data as in this example.

Discussion

The eight other chapters of this report provide the detailed results of our investigation, and demonstrate how we dealt with our main aims of providing an inventory of invertebrates and of suggesting protocols for future monitoring to measure changes. Chapter 2 (Species living on the rocky intertidal platforms in Ningaloo Marine Park) provides the start of the inventory,

listing 289 species found so far. The distribution of individuals among the species makes it certain that the number of species will continue to increase as more sampling is conducted, because most species are rare. It is probably that no single study can hope to find all the species that occur even in the small area that these shoreline, intertidal, rocky platforms occupy. Based on the precise identifications for the most abundant groups, the gastropods, it is unlikely that many species are unique to Ningaloo Marine Park because the 3 of 122 species that had distributions restricted to Ningaloo Reef have wider Indian Ocean and Indo-West Pacific distribution, and most species have distributions that extend to other states. Because more species are restricted to the northern or southern parts of the Park than are shared between the two parts, future studies need to include sites along the length of the Park in order to capture the full biodiversity of the invertebrates on intertidal platforms.

The distribution and abundance of several conspicuous or abundant of these 289 species are the focus of three chapters: (Chapter 4 Cowries on rocky intertidal platforms at Ningaloo Marine Park; Chapter 5 Evidence of large, local variations in recruitment and mortality in the small giant clam, *Tridacna maxima* (Röding, 1798), at Ningaloo Marine Park, Western Australia; and Chapter 6 Spatial and temporal variability in abundance of 15 selected species of invertebrates at 18 sites in Ningaloo Marine Park, 2007 and 2009). Cowries are conspicuous but rare, small giant clams are unusual for occurring so abundantly intertidally relative to their occurrence elsewhere, and the 15 species selected because of their high abundance nevertheless vary greatly in density among sites. The common theme established by these accounts of individual species is substantial spatial heterogeneity, coupled with less, but sometimes considerable, temporal heterogeneity. Not surprisingly, the prognosis for our ability to measure differences and detect changes against this background of variation is poor, and presents a challenge for future monitoring programs.

Chapter 7 (Multivariate analyses of spatial and temporal variation of assemblages of macroinvertebrates at Ningaloo Marine Park, 2007 and 2009) takes up the theme of estimating spatial and temporal variability but instead of focusing on individual species, considers the entire assemblage of invertebrates, some features of which were introduced in Chapter 2.

We tested some of the consequences of the spatial and temporal variability discovered in the analyses in Chapters 4, 5, 6, and 7 on the ability of studies of intertidal invertebrates to detect differences between levels of protection provided by Sanctuary Zones. One suggestion from power analyses, presented in a milestone report, was at least four sites per level of Sanctuary Zone (In or Out). Chapter 9 (Comparative methods for the monitoring of sanctuary zones on rocky intertidal platforms at Ningaloo Marine Park) tried this idea, and indeed found some differences between the two sets of four sites on either side of the northern boundary of Jurabi Sanctuary Zone (Figure 4). As well, using simulations with selected subsets of data, this intensive study examined how several ways of reducing sampling effort within sites still provided robust tests of the differences between inside and outside the sanctuary zone.

Large spatial variation that seems pervasive in our study of the invertebrates could be related to the nature of the intertidal platforms themselves, and their surroundings. Chapter 3 (Do environmental variables explain differences in macroinvertebrate assemblages between intertidal rocky platforms?: a pilot study) and Chapter 8 (Linkages between intertidal invertebrate assemblages and shore platform morphology in the Ningaloo Marine Park, Western Australia) considered this possibility, and both were successful in finding environmental variables, measured at several spatial scales at each site, that were correlated with the composition of the assemblages of invertebrates at each site. Potentially, this means that the spatial and temporal variation associated with morphology of the platforms can be removed to refine the comparisons of changes and differences associated with the sanctuary zones. Furthermore, in light of the six categories of intertidal platforms defined by Chapter 8, selection of additional sites, matched for morphological category, is now possible.

Acknowledgements

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Table 1. Intertidal rocky platforms in Ningaloo Marine Park sampled for invertebrates in 1 m² quadrats. Seventeen sites are in 8 of the sanctuary zones, and 15 sites are outside sanctuary zones. In 2009, all sites sampled by quadrats were also visited in December to measure physical variables. In 2010 for the sampling of giant clams, the sites marked with ¹ were not exactly where the quadrat sampling was done, and with ² involved a second site immediately south.

Sites (* in sanctuary zone)	Latitude S	Longitude E	2007 quadrats	2008 quadrats	2009 cowries and physical	2009 quadrats	2010 quadrats	2010 giant clams
Mildura Wreck*	21°47'6.30"	114° 9'54.52"	27 July	15 November	10 February	20 July		24 August
Mildura Wreck West*	21°47'9.05"	114° 9'44.85"	27 July		10 February	20 July		
Surfers North*	21°47'13.05"	114° 9'35.84"	28 July		11 February	24 July		29 August
Surfers South*	21°47'26.16"	114° 9'14.37"	28 July	15 November	11 February	25 July		25 August
Jurabi Out 2	21°50'44.64"	114° 2'10.14"		18 November	12 February	23 July	18 February	26 August
Jurabi Out 3	21°50'48.00"	114° 2'0.02"					15 February	
Jurabi Out 4	21°50'51.00"	114° 1'55.80"					19 February	
Jurabi Out 1	21°50'51.78"	114° 1'51.30"	29 July	13 November	9 February	22 July	13, 14 February	26 August
Jurabi In 1*	21°50'57.63"	114° 1'33.43"	29 July	18 November	10 February	25 July	15 February	22 August
Jurabi In 2*	21°51'1.25"	114° 1'26.81"		14 November	10 February	26 July	16 February	28 August
Jurabi In 4*	21°51'4.50"	114° 1'26.40"					17 February	
Jurabi In 3*	21°51'6.13"	114° 1'21.89"				29 July	17 February	27 August ¹
Mangrove Bay*	21°57'40.88"	113°56'25.43"	30 July	16 November	11 February	23 July		
Mangrove Point*	21°57'50.14"	113°56'24.78"		17 November	11 February	23 July		
Mandu South Cobble*	22° 8'43.16"	113°52'12.04"	31 July		12 February	21 July		23 August
Mandu South Flat*	22° 8'45.01"	113°52'11.25"	31 July		12 February	21 July		
Pilgramunna	22°11'39.48"	113°51'17.38"	1 August		12 February	22 July		
Yardie Creek North	22°19'36.17"	113°48'31.95"			13 February	28 July		
Yardie Creek South	22°19'42.12"	113°48'29.52"			13 February	28 July		
Bateman Bay Out 2	23° 2'17.90"	113°49'42.98"				18 September		
Bateman Bay Out 1	23° 2'37.76"	113°49'39.20"	3 August			18 September		
Bateman Bay In*	23° 2'58.41"	113°49'24.34"	2 August			19 September		1 September
Coral Bay South*	23° 9'24.01"	113°45'59.89"	4 August			17 September		31 August
Coral Bay North*	23° 9'11.32"	113°46'6.00"	3 August			17 September		2 September ²
Elles In*	23°26'0.79"	113°46'52.76"				21 September		5 September
EllesOut	23°26'16.14"	113°46'48.08"				20 September		6 September
Gnaraloo Bay Out 2	23°45'36.72"	113°33'43.14"				22 September		9 September ¹
Gnaraloo Bay Out 1	23°45'47.82"	113°33'30.24"	6 August			22 September		8 September
Gnaraloo Bay In 2*	23°46'13.93"	113°32'15.93"				23 September		
Gnaraloo Bay In 1*	23°46'19.75"	113°32'10.30"	5 August			22 September		
Three Mile North	23°52'13.51"	113°29'48.00"				25 September		12 September
Three Mile In 2	23°52'30.39"	113°29'40.80"				24 September		11 September ¹
Three Mile In 1	23°52'32.00"	113°29'38.68"	7 August			23 September		
Three Mile Out 1	23°52'33.00"	113°29'37.63"	7 August			23 September		
Three Mile Out 2	23°52'45.54"	113°29'25.42"				25 September		13 September

Table 2. Sites in relation to sanctuary zones, and nature of protection. Regions (shown in Figure 1) and sites are listed in order from north to south. * indicates sanctuary zones which do not extend to shore, so the sites are not strictly in the sanctuary zone; ** indicates that the shoreline is a “Special Purpose (Shore-based Activities) Zone; *** indicates a site used to study giant clams only. Table 2 provides exact locations of the sites

Region	Sanctuary Zone	Sites Inside Zone	Location and Sites Outside Zone
B	Lighthouse Bay**	Mildura Wreck Mildura Wreck West Surfers North Surfers South	
	Jurabi**	Jurabi In 1 Jurabi In 2 Jurabi In 4 Jurabi In 3	North of northern boundary: Jurabi Out 2 Jurabi Out 3 Jurabi Out 4 Jurabi Out 1
C	Mangrove Bay	Mangrove Bay Mangrove Point	
D	Mandu	Mandu South Cobble Mandu South Flat	South of southern boundary: Pilgramunna
	Osprey Bay		South of southern boundary: Yardie Creek North Yardie Creek South
E	Bateman	Bateman Bay In	North of northern boundary: Bateman Bay Out 2 Bateman Bay Out 1
	Maud**	Coral Bay North Coral Bay North no map*** Coral Bay South	
	Pelican**	Elle’s In	South of southern boundary: Elle’s Out
F	Gnarraloo Bay*	Gnarraloo Bay In 2 Gnarraloo Bay In 1	Gnarraloo Bay Out 2 Gnarraloo Bay Out 1
	3 Mile*	3 Mile North 3 Mile In 2 3 Mile In 1	South of southern boundary: 3 Mile Out 1 3 Mile Out 2

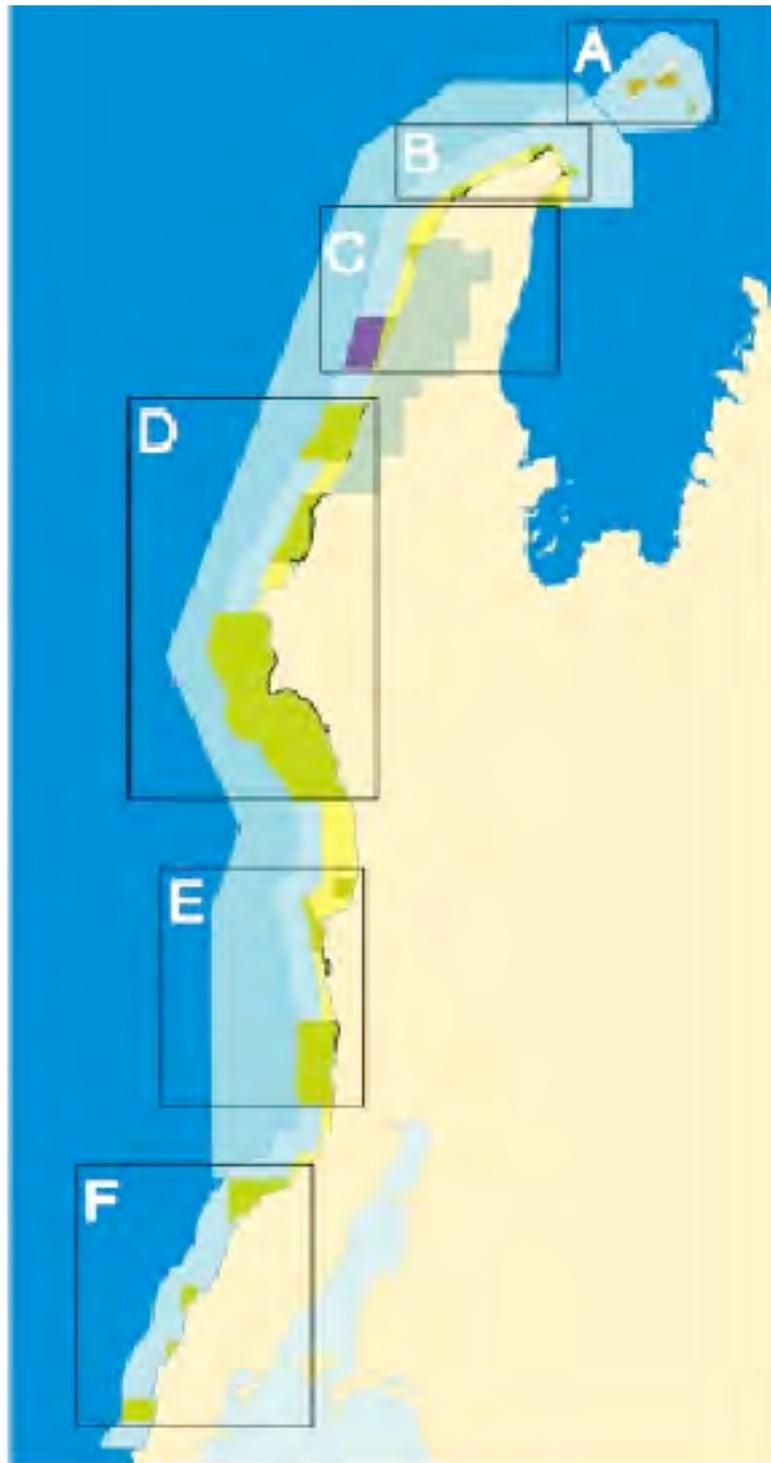


Figure 1. Regions A to F in Ningaloo Marine Park, showing the relative locations of the sanctuary zones (green) and Special Purpose (Shore-based Activities) Zones (black line). (get source - I copied it from one of the Marine Park documents).



Figure 2. The area sampled at Jurabi Out 1 is the outlined rectangle roughly 15 by 50 m. The image shows the boundaries of the Jurabi Sanctuary Zone (in red), and the parking lot at the end of Bauden Access (white rectangle on land, lower, middle right).

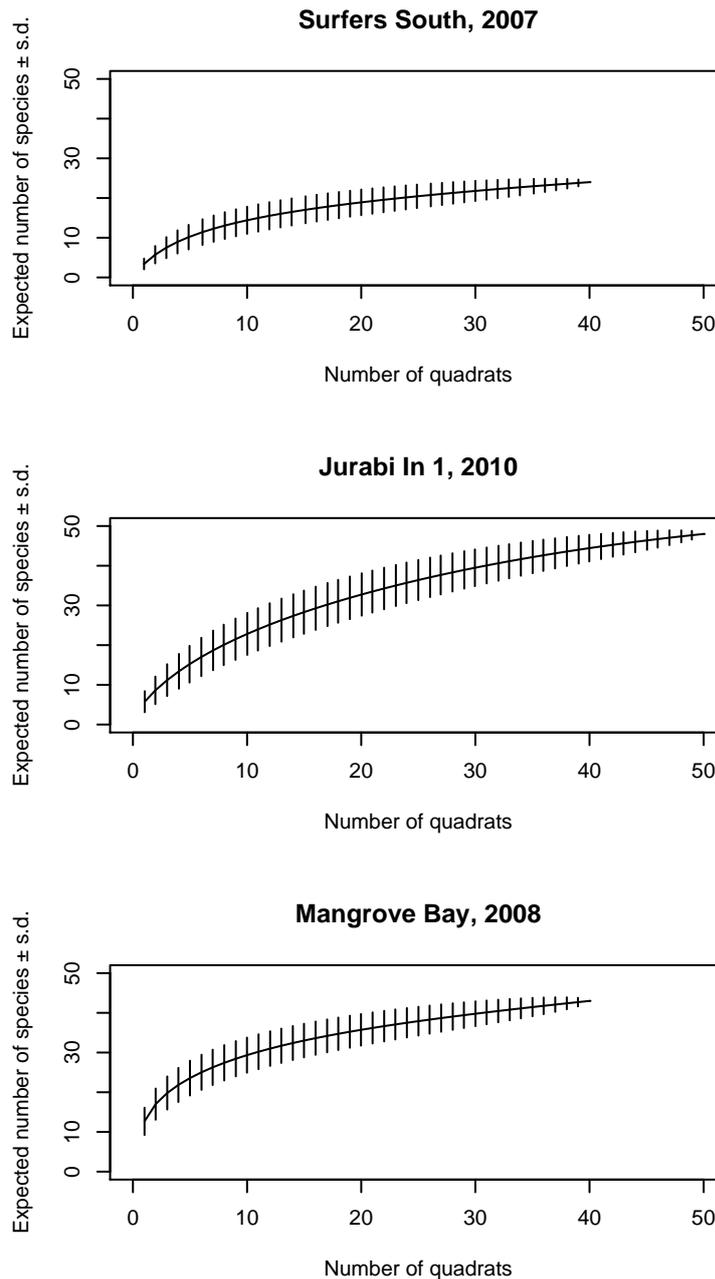


Figure 3. Species accumulation curves calculated by the “rarefaction” method by the function “specaccum” of the R package “vegan”. Surfers South, Jurabi In 1, and Mangrove Bay show the simulations based on the original data for 40, 50 and 40 1-m² quadrats, respectively in which there were 24, 43, and 48 species. The expected mean number of species for 20 quadrats ± s.d. were 18.90 ± 1.62 , 35.72 ± 1.00 , and 32.78 ± 2.66 for 100 permutations of the data.



Figure 4. Position of the eight study sites at the northern boundary of the Jurabi Sanctuary Zone plotted on Google Earth using GPS coordinates (Chapter 9: Figure 1, p. 5). Distance between the two furthest sites (In3 to Out2) is 1593 metres. The boundary of the sanctuary zone is at the small point west of Out 1.

WAMSI 3.2.2b Intertidal Invertebrates



Thirty-two sites from Mildura Wreck in the north to 3 Mile in the south. Table 1 has latitude and longitude values for the center of the sites, and the dates of visits to the sites.

Sites in Lighthouse Bay Sanctuary Zone



These sites are reached from the paved road to the Mildura Wreck at North West Cape, and are between the two main parking lots close to the Surfers South and Mildura Wreck sites.

Mildura Wreck

21°47'6.30"S

114° 9'54.52"E



Photo by Todd Bond 2009

The site is reached from the main parking lot by way of the eastern path. The site is seaward and to the left of the rock in the image above; another view of rock and site is in the next image.



Photo by R. Black November 2008

Mildura West

21°47'9.05"S

114° 9'44.85"E



Photo by Todd Bond 2009

This site is to the west of Mildura Wreck site by about 300 m west, offshore from a low rocky notch on the upper shore. The next image is from the shore looking out to the site.



Photo by R. Black February 2009

Surfers North

21°47'13.05"S 114° 9'35.84"E



Photo by Todd Bond 2009

This site is about 290 m west and south from Mildura West, or about 725 m north of Surfers South. It can also be reached from a very sandy track (best walked rather than driven) from the main road.



Photo by Todd Bond 2009

This view from the site is north towards the point behind which are the Mildura West and Midura Wreck sites.

Surfers South

21°47'26.16"S 114° 9'14.37"E



Photo by Todd Bond 2009

This view from the platform shows the notch on the shore. Access is from the path from the parking lot just to the right of picture. The parking lot is the third main (fenced) one from the turn off from the main road, and the last one before the end of the paved road and access to the Mildura Wreck and Mildura West sites. Another view in the image below is from the sampling in 2008. The site is seaward from these rocks on the platform seen on the right of the image.



Photo by R. Black 2008

Jurabi Sanctuary Zone



These sites are centered around the parking lot at Bauden Access where the Jurabi Out 1 site is. The other sites can be reached by walks along the beach. The sanctuary boundary is close to the rocky point west of Jurabi Out 1 site. Jurabi Out 4 and Out 3 are between the other Out sites (see Table 1 for exact locations). Jurabi In 4 is south of and adjacent to Jurabi In 3.

Jurabi Out 2

21°50'44.64"S 114° 2'10.14"E



Photo by Todd Bond 2009

This site is just shoreward of the line of the breaking wave in the middle of the view. It is about 550x m north of Jurabi Out 1, but can also be reached from the second parking lot north of the Bauden Access parking lot that is closest to Jurabi Out 1.

Jurabi Out 1

21°50'51.78"S 114° 1'51.30"E



Photo by Todd Bond 2009

This site is in the shallow water just above the heads of the persons in the image. The site is at the end of the path leading from the parking lot at Bauden Access. The next image looks south from the upper shore. The site is to the right in the image.



Photo by R. Black August 2007

Jurabi In 1

21°50'57.63"S

21°50'57.63"S



Photo by Todd Bond 2009

This view looks back (north and east) at the rocky point where the boundary to the sanctuary zone is. The site is the first section of platform that abuts the upper shore and a small section of rocks close to shore are higher than the seaward platform. At all the Jurabi In sites, the amount of sand on the shore has varied a lot among our visits and recognizing the sites at higher tides is difficult.

Jurabi In 2

21°51'1.25"S

114° 1'26.81"E



Photo by Todd Bond 2009

This view from the site looks shoreward and to the south. The site is east of the termination of the large dune seen in right half of this view. The green hummocks in the left half of the view are the landmarks for this site. It is about 220 m from Jurabi In 1, and is just west of the second section of platform attached to the shore from the rocky point. It too has higher rocks shoreward at the eastern boundary of the site.



Photo by Todd Bond 2009

This view from the site shows the end of the dune at the right and the green hummocks in the middle. The higher rocks at the

Jurabi In 3

21°51'6.13"S

114° 1'21.89"E



Photo by Todd Bond 2009

Jurabi In 3 is 200 m along the shore from Jurabi In 2. This image is from the top of the notch on shore, and the image below looks from the shore westward.



Photo by Todd Bond 2009

Mangrove Bay Sanctuary Zone



From the Mangrove Bay parking lot, these sites can be reached by taking the northern path and walking across the large flat out to the offshore site. Mangrove Point site can be reached by taking the path to the west and following the shore to the tip of the point. The two sites can be reached from each other by waling along the platform from the offshore site to the south-west and then crossing the narrow channel to the platform that extends from the point. At higher tides, the flat north of the point had had lots of large stingrays.

Mangrove Bay 21°57'40.88"S 113°56'25.43"E to 21°57'42.88"S 113°56'23.47"E



Photo by Todd Bond 2009

This site is seaward of the three stacks lining the shoreward side of this long platform reached by crossing the large flat between the shore and this higher platform. This view above is from the middle stack looking south-west. The southern part of the site is the right part of this view. The Mangrove Point site can be reached by walking south-west past the stack and then south-east towards the point across a narrow channel between the two platforms. The image below looks from the middle stack north north-east toward the northern stack. The northern part of the site is to the left.



Photo by Todd Bond 2009

Mangrove Point

21°57'50.14"S 113°56'24.78"E



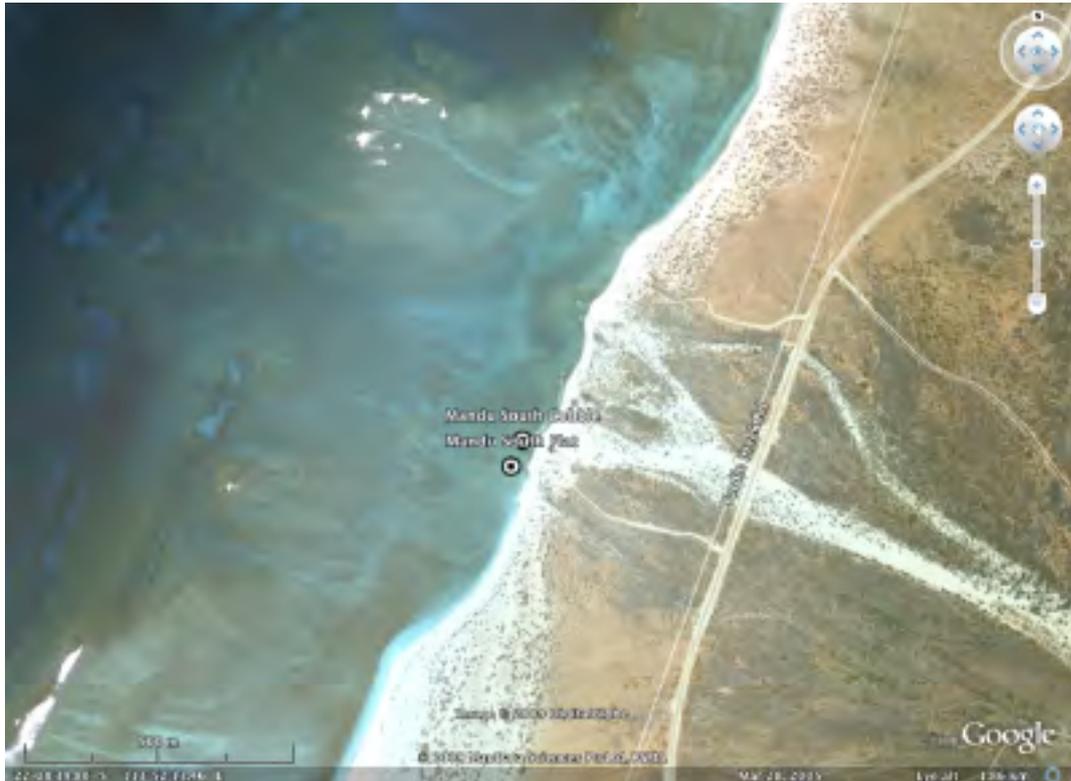
Photo by Todd Bond 2009

This is a view from the site towards the end of the point. The site is 60 m from shore. The image below show the texture of the platform is uneven with lots of 1-2 m long depressions.



Photo by Todd Bond 2009

Mandu Mandu South



These sites are reached by the track just south of where Mandu Mandu Creek crosses the main road with a parking lot just behind the large berm of cobbles.

Mandu South Cobble

22° 8'43.16"S

113°52'12.04"E



Photo by Todd Bond 2009

This is a view from the cobble berm, and the site is seaward of the exposed cobbles in the middle right of the view. The site is off shore from the tidal pool behind the cobble berm, and south of the post embedded in the northern part of this cobble-field.

Mandu South Flat

22° 8'45.01"S

113°52'11.25"E



Photo by Todd Bond 2009

This is a view from the cobble bern towards the site which is on the higher part of the platform that can be seen above the exposed rock on the shore extending seaward towards a ridge of higher platform at the seaward edge of the platform. The next image is taken from the site, looking seaward to the ridge of rocks beyond the site.

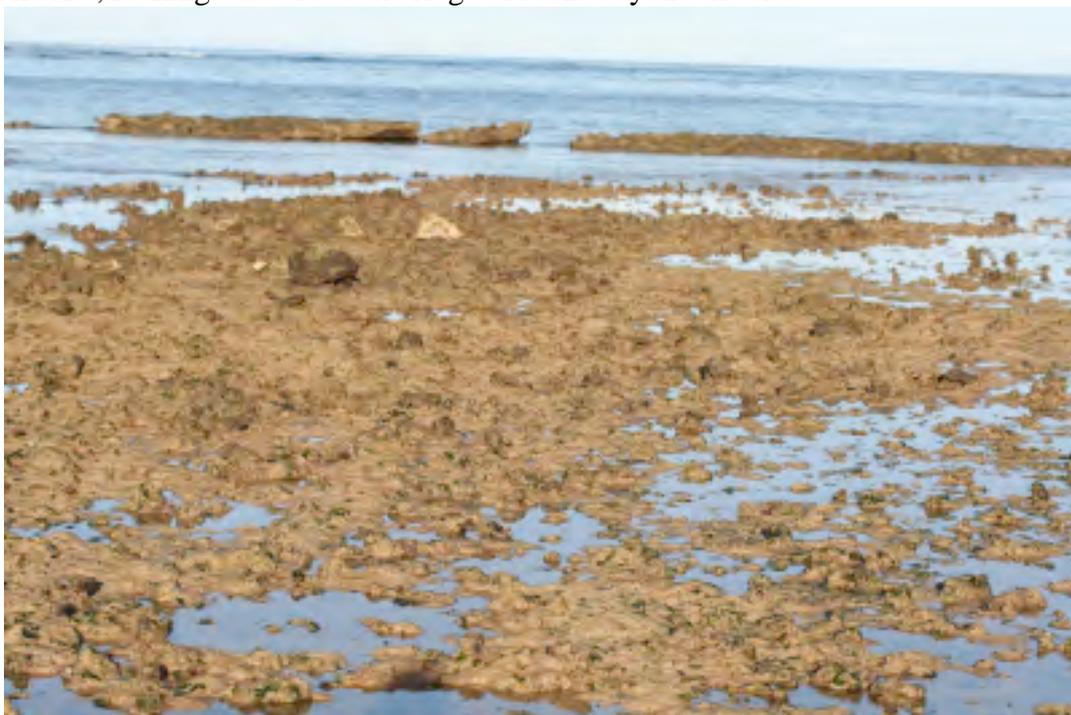


Photo by R. Black February 2009

Pilgramunna



This site is reached from the Pilgramunna Creek turnoff. At low tide, there is parking on the south side of the creek where the campers are.

Pilgramunna

22°11'39.48"S 113°51'17.38"E



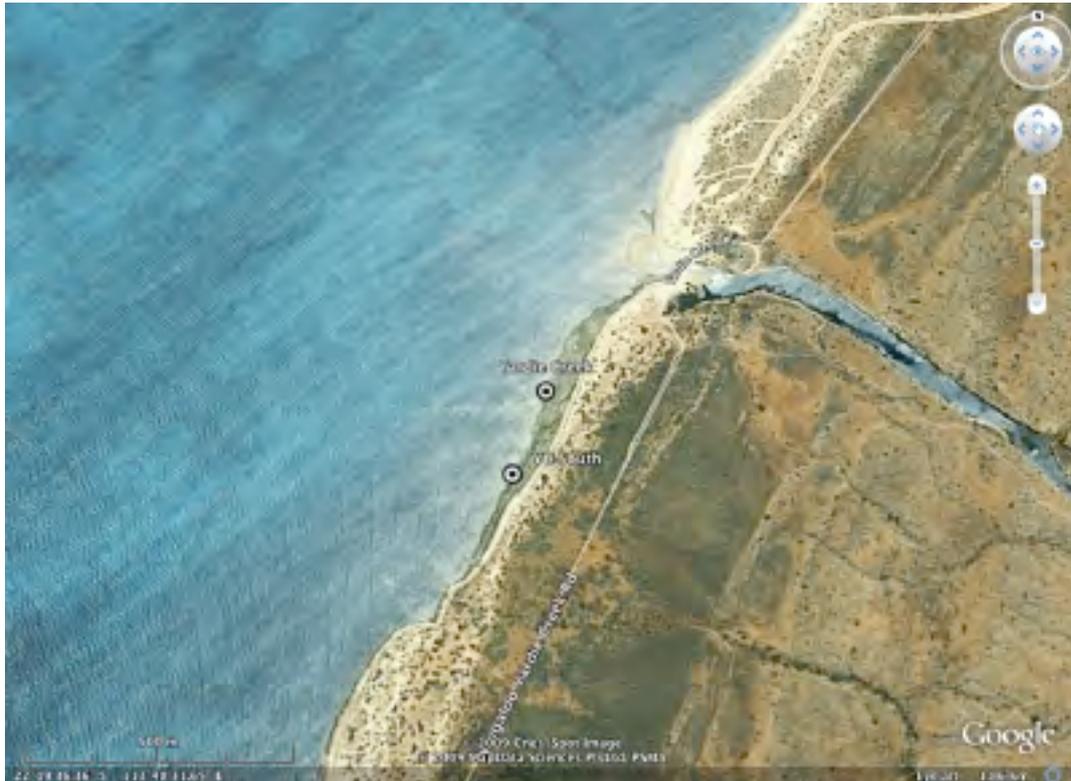
Photo by Todd Bond 2009

This site is south of the rocky point that is of the creek mouth. It is north of the shallow pool seen just above the edge of the notch in the middle of this view, and does not extend south into a lower section of the platform. The image on the next page is a view from the shore. The rocky point is out of the view to the right. The rim of exposed rocks at the seaward end of the platform are visible seaward of the figures in the image.



Photo by Todd Bond 2009

Yardie Creek



The Yardie Creek sites are reached from the parking lot at the end of the road (before the 4WD track across the creek that may or may not be crossable at low tide). The sites are on a huge platform south of the creek, reached by walking along the shore (~460 m from the parking lot-side of the creek to the northern site)



Photo by Todd Bond 2009

The site is, like all the others, in the middle of the platform some distance from the shore, beyond the lower distribution of the very numerous ceriths. The image below shows the texture of the platform more clearly although it is taken from the high tide mark.



Photo by Todd Bond 2009

Yardie Creek South

22°19'42.12"S 113°48'29.52"E



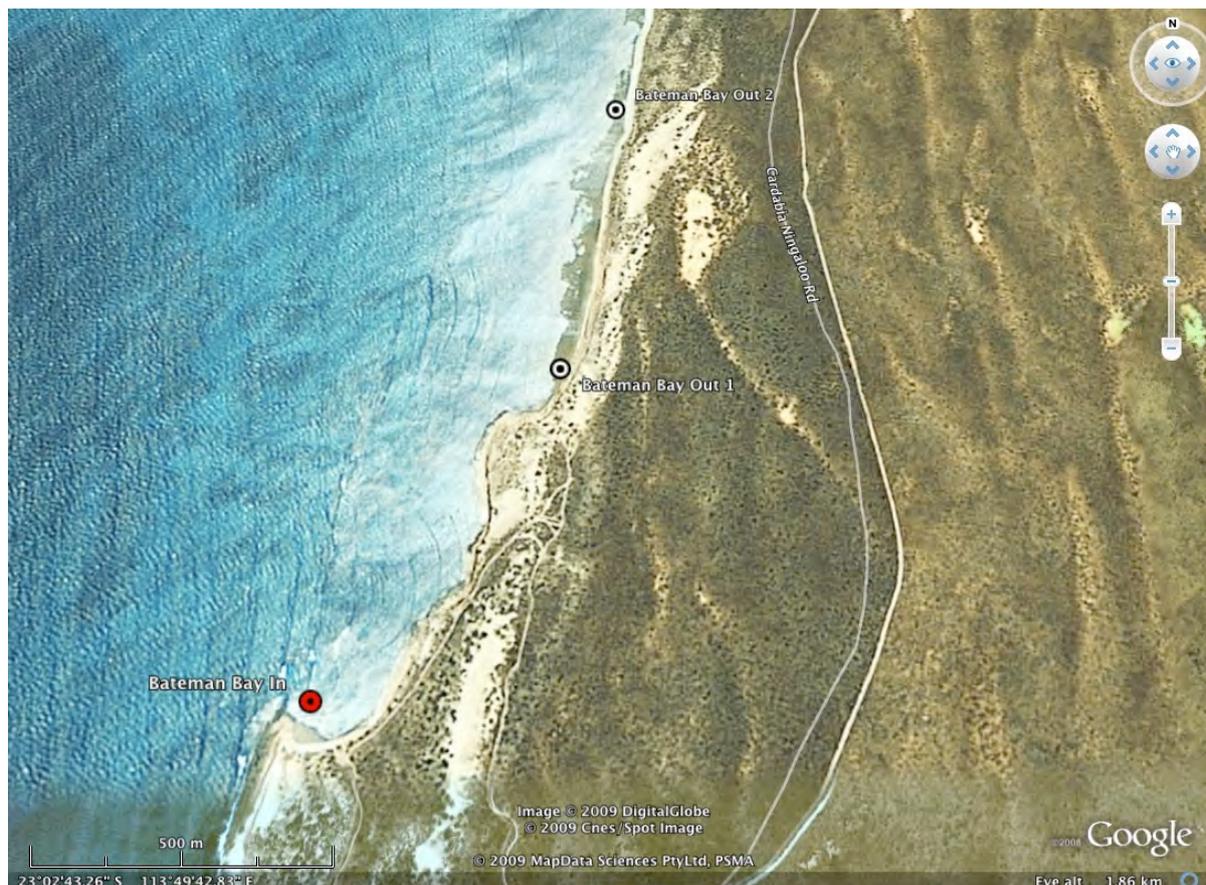
Photo by Todd Bond 2009

This is a view south-west from the site in the middle of the platform towards its western end. This site is about 160 m westward from the northern site. The image below shows a seaward view of the site.



Photo by Todd Bond 2009

Bateman Bay outside sanctuary zone



Access to these sites is from the paved Coral Bay Road, turning north along the xxxxxxxxx Road for several kilometers.

To reach the two northern sites, veer left where there is a large triangle of intersecting tracks to reach the two northern sites (not shown in the image above). From this intersection the track is very sandy so tires need to be at 20 psi. The two sites outside the sanctuary zone are at a place called Cardiac Hill on which the boundary posts are situated. The end of the Cardiac Hill track is a loop where we parked. Walk to the boundary marker and then turn south to get down the hill, which is very steep.

To reach the Bateman Bay In site, see page 23. There is a track that links Cardiac Hill to Dog Rock along the coast, but the track is very sandy and hilly. We drove out to the Cardabia Ningaloo Road, turned south and entered the track to the coast marked by the small triangle of tracks, as seen on page 22.

Bateman Bay Out 2

23° 2'17.90"S 113°49'42



Photo by Todd Bond 2009

This site is a 610 m walk north from Bateman Bay Out 1 site. The platform here is narrower than further south, and the day we sampled there was a ridge of sand built up on the platform as shown in the photo. The site was to the right of this image. As can be seen in the Google Earth image, the site is along the shore from the northern end of the sandy dune and as viewed from Batemena Bay Out 1 site, is beyond the small point (which is to the left of the image above).



Photo by Todd Bond 2009

This image shows the texture of the site with evidence of sand accumulating on the surface in the foreground.

Bateman Bay Out 1

23° 2'37.76"S

113°49'39.20"E



Photo by Todd Bond 2009

This is a view from the site back towards Cardiac Hill on the right which has a sanctuary zone post on its top. Access is from the west side of the hill. The image below shows the texture of the platform.



Photo by Todd Bond 2009



Photo by Anne Brearley August 2007

Bateman Bay Sanctuary Zone (northern boundary)



Access to these sites is from the paved Coral Bay Road, turning north along the Cardabia Ningaloo Road for several kilometers.

To reach the two northern sites, veer left where there is a large triangle of intersecting tracks to reach the two northern sites (northern one is not shown in the image above). From this intersection the track is very sandy so tires need to be at 20 psi. The two sites outside the sanctuary zone are at a place called Cardiac Hill on which the boundary posts are situated. The end of the Cardiac Hill track is a loop where we parked. Walk to the boundary marker and then turn south to get down the hill, which is very steep.

To reach the Bateman Bay In site we used another track off the Cardabia Ningaloo Road. There is a track that links Cardiac Hill to Dog Rock along the coast, but the track is very sandy and hilly. We drove out to the Cardabia Ningaloo Road, turned south and entered the track to the coast marked by the small triangle of tracks, as seen in the image above.

Bateman Bay In

23° 2'58.41"S

113°49'24.34"E



Photo by Todd Bond 2009

This site is directly off the beach at the car park at Dog Rock which this view shows. The site is this side of the point of rocks in the middle, and along the platform covered by water to the right of this image. The image below is taken from the hill to the left of this image looking north. The ridge of rocks is at the left. The parking place is to the right of the image.



Photo by Todd Bond 2009.

Maud Sanctuary Zone



These sites are south of the Coral Bay townsite. This image predates the construction of the new groyne and boat launching ramp and huge parking lot. The northern site can be reached from one of the coastal tracks off the paved road to the parking lot, or from the DEC storage building at the townsite. the southern site is reached from the parking lot.

Coral Bay North 23° 9'11.32"S 113°46'6.00"E



Photo by Todd Bond 2009

This is a view south towards the groyne seen at the horizon to the middle of the image. This platform is just a small oval projecting from the shore. In 2010, giant clams (*Tridacna maxima*), were sampled along the narrow platform to the south (towards the groyne) which is site Coral Bay North no map. The image below shows the texture of the platform.



Photo by Todd Bond 2009

Coral Bay South

23° 9'24.01"S

113°45'59.89"E



Photo by Todd Bond 2009

This image is taken from the edge of the parking lot at the launching ramp. There are two figures on the site at the middle right of the platform. See the next image for a view from the site.



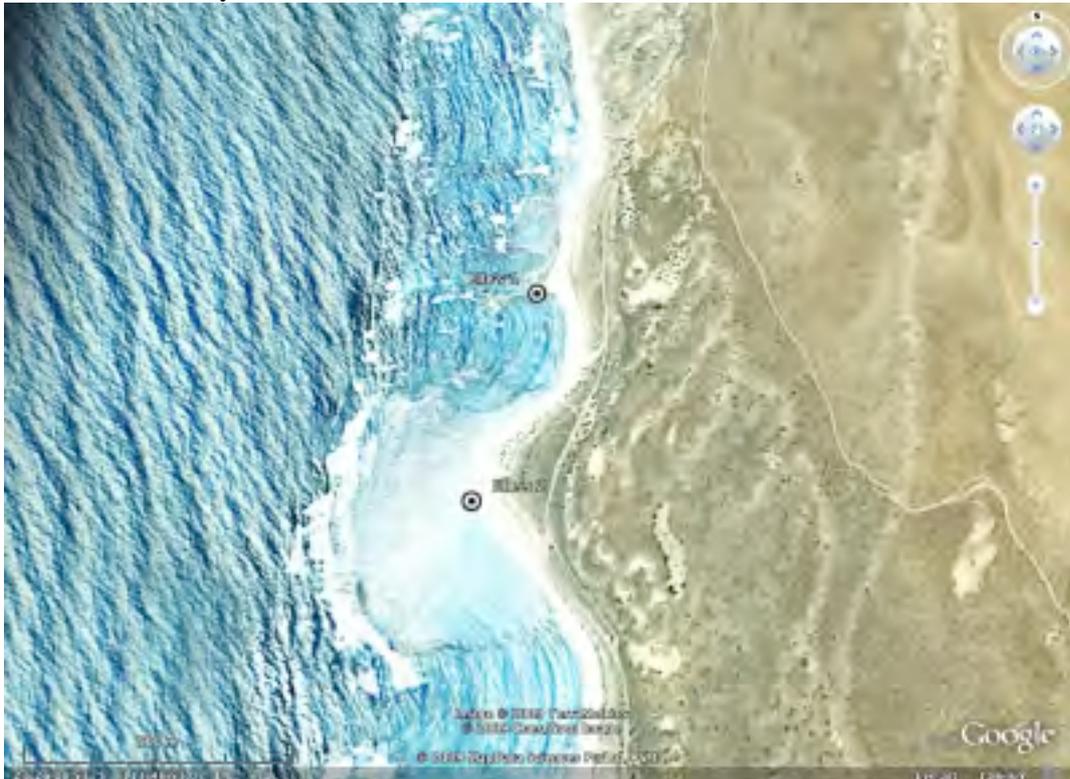
Photo by Todd Bond 2009

The site is seaward from several large rocks broken off the notch. The platform is narrow, and this view looks south. The groyne is north along the shore from here about 150 m. The image below shows the texture of the platform.



Photo by Todd Bond 2009

Pelican Sanctuary Zone



These sites are reached from Warroora Station reached by the Warroora East Road. The track goes north from the station, and we followed turned west at an old, almost illegible sign “Elles”. The northern site is a very high platform visible from the track after it turned south along the coast. We parked at a wide part of the track with some star pickets. The southern site is at the end of the track going south where the station gate is locked.

Elles In $23^{\circ}26'0.79''S$ $113^{\circ}46'52.76''E$



Photo by Todd Bond 2009

This site is along the platform at the base of the inlet seen in the middle of this image.



Photo by Todd Bond 2009
This platform was very high and very flat.

Elles Out

23°26'16.14"S 113°46'48.08"E



Photo by Todd Bond 2009

This is a view from the site towards shore. The platform is connected to shore to the left some distance, but separated from shore here by a channel. The southern boundary marker of Pelican Sanctuary Zone is close to where the platform joins the shore (to the right of the right edge of this image). The parking place is behind the dune at the right side of the image. As the image below shows the platform had many giant clams.



Photo by Todd Bond 2009

Gnaraloo Bay



These sites are accessed from Gnaraloo Station. The track goes north from the station and the track parallel to the coast shown in the image above branches to the east about 5.2 km from the station (past the northern end of the airstrip), or 1.3 km from the gate leading to the parking area at the boat launching place. This track ends at a locked gate, and the parking place is before the locked gate. This place is called “6 mile”, I think. Gnaraloo Bay North 1 is visible from the top of the dune at the parking area. Gnaraloo Bay North 2 is a 500 m walk north-east along the beach.

Gnaraloo Bay North 2 23°45'36.72"S 113°33'43.14"E



Photo by Todd Bond 2009

This site is on a narrow platform seaward from a rocky notch on the shore. The next image shows the texture of the platform.



Photo by Todd Bond 2009

Gnarraloo Bay North 1

23°45'47.82"S

113°33'30.24"E



Photo by Todd Bond 2009

This site is on a high platform in the middle of its length to the west of eastern end that is connected to the shore. Parts of the platform have high densities of urchins as the next image shows.



Photo by Todd Bond 2009

Gnarraloo Bay Sanctuary Zone



These sites are reached from the parking lot at the end of the track north from the station. The walk from there, around the point and south along the shore is about 1100 m to the northern site. The southern site is another 251 m.

Gnarraloo Bay South 2 23°46'13.93"S 113°32'15.93"E



Photo by Todd Bond 2009

This is a view from the shore at the site to the north to the point. The site is close to the beginning to the platform. The image on the next page shows the texture of the platform.



Photo by Todd Bond 2009

Gnarraloo Bay South 1 23°46'19.75"S 113°32'10.30"E



Photo by Todd Bond 2009

This image and the next one are at the southern site. The image above looks north towards the point, and the next one looks south



Photo by Todd Bond 2009



Photo by Todd Bond 2009

This shows the texture of the platform on a rising tide.

3 Mile Sanctuary Zone



These sites are all close to the 3 Mile camping ground. We reached the southern sites from the track that branches to the south along the fence line marking the southern boundary of the camping area. We parked at a turnout at where the fence meets the coast to get to the middle sites. the northern site can be reached by walking along the beach or by entering the campground, and parking behind the dune where there is a boat-launching place. The southern site we reached by walking north along the beach from a parking spot about 350 m south of the site.

Three Mile North 23°52'13.51"S 113°29'48.00"E



Photo by Todd Bond 2009

This is a view back toward the campground (trees on the horizon and a tall notch on the shore). The site is offshore 90 m to the right of this image some distance to a slightly raised portion of the platform with many giant clams and corals, as seen in the next image.



Photo by Todd Bond 2009

Three Mile In 2

23°52'30.39"S 113°29'40.80"E



Photo by Todd Bond 2009

This site is north of Three Mile In 1 and can be reached from the south, or from the north (from the end of the tracks in the campground). The platform is narrow and pitted by small pools.



Photo by Todd Bond 2009

Three Mile In 1

23°52'32.00"S 113°29'38.68"E

This site is immediately to the north of the boundary marker, i.e., to the left of this image.
Three Mile Out 1 is to the right in this image, to the south.



Photo by Anne Brearley August 2007



Photo by Anne Brearley August 2007

This image is from the top of the notch, looking down at the narrow platform of Three Mile In 1.

Three Mile Out 1

23°52'33.00"S 113°29'37.63"E



Photo by Anne Brearley August 2007

Three Mile Out 2 23°52'45.54"S 113°29'25.42"E

We parked about 300 m south of the site, and reached the shore with a walk of about 100 m. This site is approached along the sandy beach from the south northwards. The narrow platform extends from a low (for this part of the coast) notch. It has two sections, horizontal extending from the notch, and then sloping towards the seaward edge. The change in slope forms the midline of the site. The image below looks north to the site which is offshore from the rock, about 140 m from the start of the notch and narrow platform.



Photo by Todd Bond 2009



Photo by Todd Bond 2009

This view is from the notch with the edge of the white water at the break in the slope of the platform which forms the midline of the site.

Chapter 2: Species living on the rocky intertidal platforms in Ningaloo Marine Park

Introduction

A result of sampling the assemblages of macroinvertebrates on rocky intertidal platforms in Ningaloo Marine Park is an inventory of the organisms, one of our main aims. We counted all the species of macroinvertebrate in 20 1-m² quadrats at sites during 2007 to 2010. Tables 1 and 2 in Chapter 1 show the locations of the sites and the dates on which they were sampled. This account provides i) lists of species, with summaries about their overall abundance, ii) information about their occurrences in the north and south parts of the Park, iii) details for carefully identified species about their distribution beyond the Park, and iv) some statistical summaries about the species richness and species diversity in the northern and southern sites in 2007 and 2009.

Methods

In the standard sampling of sites in 2007 and 2009, the sites at Yardie Creek were separated by a long gap to the sites at Bateman Bay, so we considered that our sites represented two geographical areas within the Park. There were 17 sites in the North in Regions B, C and D, and 16 in the South in Regions E and F (Chapter 1, Table 1). We summarized various features of the occurrence of species in these two geographical areas within the Park.

To provide a view of how the numbers of species, or species richness, increased as we sampled more sites, we used the statistical program R (R Development Core Team 2009) to calculate species accumulation curves according to the “exact” method of the function “specaccum” in the package “vegan” (Oksanen *et al.* 2010). The statistical program EstimateS Version 8.2.0 (<http://viceroy.eeb.uconn.edu/estimates>) calculated the number of species expected in samples containing a particular number of individuals based on the composition of the individual quadrats. To display how individuals were distributed among the species in our samples, we used the function “radfit” in the package “vegan” (Oksanen *et al.* 2010).

Ecologically meaningful differences among assemblages involve differences in frequencies of occurrence of species, not merely their presence and absence (Jost 2007). To make use of our quantitative estimates of the abundance of each of the species, we calculated Alpha, Beta, and Gamma diversity as Numbers Equivalents, according to Jost (2007) as implemented by Charney and Record (2009) in the R package “vegetarian”. The ${}^1D_{\text{alpha}}$, ${}^1D_{\text{beta}}$, and ${}^1D_{\text{gamma}}$ indices are Jost’s (2007) numbers equivalents that are related to the standard Shannon entropy measure $H \equiv -\sum p_i \ln p_i$, where p_i is the proportion that the i^{th} species makes up of the total individuals in the sample of the assemblage, and the summation is over the S species in the assemblage. The numbers equivalent index, represented by 1D , of H is simply $\exp(H)$. This is interpreted as the numbers of equally abundant species that would have given the same value of the index as the number of (unevenly abundant) species in the original sample. The three numbers equivalent indices are related by ${}^1D_{\text{alpha}} \times {}^1D_{\text{beta}} = {}^1D_{\text{gamma}}$, and these indices have five basic properties that ecologists expect of diversity indices (Jost 2007). Thus, in a set of data representing the abundances of species at several sites, ${}^1D_{\text{gamma}}$ represents the number of equally abundant species that would produce the same index as the species in the pooling of the abundances from all the sites, that is, without knowledge of the site from which any individual came. ${}^1D_{\text{alpha}}$ is the average index when the calculations are done for each site individually, so it represents the number of equally abundant species that would give the index at an average site. Importantly, in terms of how much the assemblages differ among sites (beta diversity), ${}^1D_{\text{beta}}$ is the effective number of distinct assemblages in the set of sites (i.e., the number of assemblages with mutually exclusive species in that set of sites).

Another way of considering diversity of species in quantitative estimates of the relative abundance of species in collections is a statistical procedure called rarefaction. We calculated the number of species in a collection of 1000 individuals according to Heck *et al.* (1975) and Hurlbert, S.H. (1971) as implemented in function “rarefy” in the R package “vegan”(Oksanen *et al.* 2010).

We used the R package “vcd” (Meyer *et al.* 2006, 2009, Zeileis *et al.* 2007)) and the functions “coindep_test” and “mosaic” to present results of contingency tests.

Results

Our standard sampling in 2007, 2008, and 2009 yielded 243 categories of macroinvertebrates in 1292 m². The richest taxon was gastropod molluscs with 114 species, and we were able to identify these species. The number of species in other groups, less well identified, but nevertheless separate taxa, were 41 cnidarians, 28 echinoderms, 24 crustaceans, 18 bivalves, 10 chiton, and 8 from unusual groups. In February 2010, we sampled eight sites at the northern boundary of the Jurabi Sanctuary Zone, 4 inside and 4 outside the zone. These additional samples from 452 m² at Jurabi, produced a further 46 species not seen in the earlier sampling (13 gastropods, 9 cnidarians, 5 echinoderms, 4 crustaceans, 1 bivalve, 2 chitons, and 12 unusual). Table 1 lists all these macroinvertebrates with their identifications to species, or with our code names. Within each taxonomic group, the species are listed in order of numerical abundance. Among these 289 species found in 1744 m², 92 or 32% of species, occurred as singletons in the whole collection of 31,059 individuals (0.29% of individuals).

The taxa and the most abundant species were Bivalvia (*Brachidontes ustulatus*, *Septifer bilocularis* and *Tridacna maxima*), Gastropoda (*Serpulorbis siphon*, *Strombus mutabilis*, *Cypraea caputserpentis*, *C. moneta*, *Cronia avellana*, *Morula uva*, *Conus sponsalis*, and *Conus dorreensis*), Pulmonata (*Siphonaria* sp.), and Echinoidea (*Echinometra mathaei*). The first two species of bivalve are small, suspension feeding mussels that form tight clumps attached to the surface of the platform and so are at high density in small areas. Of the gastropods, the first species is attached to surfaces and uses mucus strings to feed on particles in the water. The others are mobile, stromb and the two cowries being herbivores, and the others predators. None exceed a few centimeters in length. The pulmonate is a small grazing limpet that reaches high densities on patches of bare rock. The echinoid (sea urchin) was very abundant at a few sites. Some of these species are considered in more detail in other parts of this report.

The occurrence of species in 2007 and 2009, and in the two geographical areas of the Park showed some differences in the species richness of the fauna (Table 2). The overall numbers

of species separately in 2007 and 2009, and in both years together, were 117, 187, and 219 respectively, reflecting, in part, the increased sampling effort. The numbers of species present in both the North and South areas were 43, 53, and 70, or 37, 28, and 32% of the totals, indicative of the large number of species represented by few individuals. The number of species shared between 2007 and 2009 was 85 of 219 or 39%. As judged by the presence and absence of species, the sites in the North and South differed by having a considerable number of species that were unique to each area (Table 2), although many of the unique species were represented by species represented by single individuals. The numbers in parentheses in Table 2 omit these singleton species, and the percentages of shared species without these increased, especially for 2007 (53% compared with 36%) .

One way of displaying the relative abundances of species in collections is plotting Dominance/Diversity or Rank-Abundance Dominance curves with the abundance of each species on the Y-axis with the species on the X-axis in decreasing order of abundance. Ecologists have suggested several mechanisms that might determine how individuals are allocated among species and produced mathematical models to make predictions about the shape of the Rank-Abundance Dominance curves, although a fit to any of the models cannot imply that the mechanism actually operates. Here we consider the mathematical models as empirical descriptions representing different patterns that the Rank-Abundance Dominance could have. We pooled our samples into four groups, from the northern and southern sites in each of 2007 and 2009 to display the curves (Figure 1). The Mandelbrot model fit these four sets of data best, but similar plots for the individual sites in 2009 showed best fits for the Preemption model (4 sites) and the Zipf model (11 sites) as well as the Mandelbrot model (18 sites), so the pooling of sites hid some of the variety in shapes of these curves. The main feature of Figure 1 is the large number of species represented by one individual, indicated by the long flat tail at the right end of each plot. A feature of contrast between the two geographical areas shows up at the left end of the plots. In the North the most abundant species had hundreds of individuals while in the South the most abundant species had more than one thousand individuals (see Table 1 for the abundant species).

Of the taxa that we recognized in our sampling, 124 were identified as recognized species so we could discover their recorded geographic distribution relative to their occurrence in the Park. We summarized these distributions as being “Northern” if the Park was close to the southern limit of distribution of the species, “Southern” if the Park was close to the northern limit of distribution, and “To South and North” if the limits of distribution extended well to the north and south of the Park (Table 3). There were proportionally more species with southern distributions among the species found only in the 16 sites in the south part of the Park (Figure 2).

As we conducted our standard sampling using 20 1-m² quadrats at each site, it was obvious that as we increased the number of sites sampled, both with and between our sampling in 2007, 2008, 2009, and 2010, the number of species continued to accumulate. This is a standard feature of ecological sampling of assemblages of organisms, and is summarized by “species accumulation curves” which plot the cumulative number of species against some measure of intensity of sampling. These curves rise steeply at first, but the slope decreases as sampling increases, and both the steepness of the rise and the elevation reached by the curve are informative. The curves may gradually flatten out, indicating that the sampling has discovered most species. We used the number of sites sampled as a measure of intensity of sampling, and as expected from the large number of species represented by one individual, the species accumulation curves of Figure 2 did not become horizontal at their right ends. Even with the increased effort in 2009 compared with 2007 (16 sites versus 8 sites in the south), the curves have slopes much greater than 0.0 at their right ends. However, the greater number of species per site is obvious for the south by comparing the elevations of the curves in the two years.

The numbers of individuals and number of species in the 20 1-m² quadrats varied considerably, ranging from 58 to 1369 individuals, and from 8 to 38 species in the 33 sites in 2009 (Figure 3). The species accumulation curves in Figure 3 use Individuals as the measure of intensity of sampling, but each curve has 20 points representing the 20 quadrats. The shapes of the curves and their final elevations reveal aspects of the heterogeneity of

distributions of individuals among species at all the sites, and the spread of the curves for the sites in the South displayed much more variety than the sites in the North.

Another way of viewing the occurrence of species at the sites is by taking into account the relative abundances of each species. The ${}^1D_{\text{alpha}}$, ${}^1D_{\text{beta}}$, and ${}^1D_{\text{gamma}}$ indices in Table 4 are Jost's (2007) numbers equivalents indices. By these measures, the North had more "equally abundant" species than the South in 2007 because ${}^1D_{\text{gamma}}$ was much greater as judged by the small standard errors relative to the indices themselves, but rather less distinct in 2009 when we sampled almost equal numbers of sites in the north and south. On the basis of the average number of equally abundant species per site (${}^1D_{\text{alpha}}$), rather than for the whole set of sites, the northern sites had greater alpha diversity in both years. Thus, the beta diversity, the differences among sites within the north or within the south, was greater for the south (3.8 equally distinct assemblages) than for the north (an average over 2007 and 2009 of only 2.6 equally distinct assemblages).

Considering the two regions together, there were slightly more equally abundant species in 2009 than 2007 (20.6 versus 17.6). The assemblages in the two regions represented 1.4 equally distinct communities, rather less divergence than among sites within north and south, but still representing considerable diversity between regions.

Another way of considering variety among the species is the expected number of species in a collection of 1000 individuals (Table 4). This measure showed the North had more expected species than the South in 2007 but fewer in 2009. This measure was sensitive to the large numbers of mussels (*Brachidontes ustulatus*) and ceriths (*Clypeomorus batillariaeformis*) at some southern sites in 2007 but not in 2009 (Table 1).

Discussion

The outstanding feature of the rocky intertidal platforms at Ningaloo Marine Park is that, despite their sometimes barren appearance, they have a rich assemblage of animals not

immediately obvious to a casual observer. This is because many of the macroinvertebrates are small, camouflaged, or hidden, and revealed only by careful searches of relatively small areas as in our samples of 1-m² quadrats. This fauna has representatives of most of the major invertebrate phyla and several others familiar only to experts. Molluscs make up the largest proportion of the 289 categories of invertebrates in our samples. Among the molluscs are some of the species that receive focused attention by visitors to the platforms, such as cowries, cones, giant clams, and octopods, although these represent only a tiny fraction of the animals that live on the platforms.

Coupled with the large number of species is the second important aspect of the assemblages of animals on the platforms. Most of the species are rare. Nearly one third of the species occurred as single individuals. This is not unusual in surveys of ecological communities, and our tally of 32% singletons is in the middle of the range of 8 to 72% among 72 examples reported by Coddington *et al.* (2009) for surveys of tropical arthropods. Furthermore, of the 243 species in our 2007 and 2009 sampling, only 88 had more than ten individuals in 1292 m², of which only 8 had totals of more than 1000 individuals.

The consequences of these features for future monitoring schemes or repeated surveys of the assemblages on the intertidal platforms are sobering. First, the sample-based and individual-based species accumulation curves show that our sampling scheme and most others will continue to find species not seen before. Second, any desire to find all the species in the communities of invertebrates on the platforms will have to be matched by massive effort and huge expense. Third, estimates of what invertebrates are present on intertidal platforms in Ningaloo Marine Park will require sampling many different sites.

One reassuring aspect of the recorded geographic distribution of the species shown in Table 3 is that the proportion of rare species (<10 individuals) restricted to Western Australia is the same as the proportion of the abundant species (>10 individuals - see Table 1), suggesting that the wider geographic distribution of the species is independent of the abundances in our sampling. Furthermore, these geographic distributions also suggest that there will be few species that are completely restricted to the Ningaloo Marine Park. Most of the species have

distributions that extend to other parts of Western Australia, and to other states. The exceptions were the muricid gastropod *Drupina lobata*, the cone *Conus lischkeanus*, and the buccinid whelk *Crassicantharus noumeensis* which are recorded from Ningaloo Reef or nearby only, have Indian Ocean or Indo-West Pacific distributions.

Overall, the numbers of species slightly slightly higher in the southern sites than in the northern ones for our samples in 2007, 2008, and 2009. However, the intensive sampling at Jurabi in 2010 revealed many more species, reflecting the species accumulation relationships based on the earlier sampling. In any case, overall species richness may provide an incomplete view of variety in the assemblages. Analyses of diversity take the relative abundances of the species into account. The numbers equivalents measures are consistent in ranking alpha diversity (i.e., within site) greater in the north than the south, but the beta diversity (among sites) greater in the south than in the north. Thus, if future monitoring or surveys are carried out, and if one aim to obtain a clear view of what species occur on the intertidal platforms, many sites need to be sampled along the whole length of the Park, rather than a just a few sites. This is because of the beta diversity indices indicate diversity between the north and south parts of the park, and even greater variety among sites within the south than within the north parts of the Park.

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Table 1. Categories of macroinvertebrates sampled in 1292 1-m² quadrats in 2007 and 2009, and 452 1-m² quadrats at Jurabi in February 2010.

Cnidaria

Taxon	Label	Number
Actinaria	Anemone brown	148
	Anemone green colonial	31
	Anemone sand	27
	Anemone green	6
	Anemone red-brown	1
Alcyonacea	Soft coral feathery	8
	Soft coral	3
	Soft coral 10	2
	Soft coral 6	2
	Soft coral 1	1
	soft coral 2	1
	Soft coral 3	1
	Soft coral 4	1
	Soft coral 4x	1
	Soft coral 5	1
	Soft coral 7	1
	Soft coral 8	1
	Soft coral 9	1
	Soft coral two-toned	1
	Soft coral bumps)	1
Scleractinia	Coral 2mm brown)	496
	Coral brown ?Porites)	171
	<i>Acropora</i> spp.	85
	Coral, favid)	18
	<i>Pocillopora damicornis</i> (Linnaeus, 1758)	17
	Montipora	6
	Coral unk branch small polyp	5
	Coral grey	4
	Coral brown favid	3
	Coral massive green brown	2
	Coral massive	2
	Coral brown massive 2	1
	Coral flat brown	1
	Coral irreg polyps "Platygyra"	1
	Coral massive small	1
	Coral sp. 2 (2mm)	1
Zoanthidea	<i>Palythoa densa</i> Calgren, 1954	2
	<i>Palythoa heideri</i> (Carlgren, 1954)	2
	<i>Isaurus tuberculatus</i> Gray, 1828	1
	<i>Zoanthus marshi</i> Calgren, 1954	1
	Zoanthid brown separate	1

Bivalves

Taxon	Species	Number
PTERIOMORPHA		
Archidae	Arc shell	7
Mytilidae	<i>Brachidontes ustulatus</i> (Lamarck, 1819)	6803
	<i>Septifer bilocularis</i> (Linnaeus, 1758)	1968
	<i>Lithophaga</i> sp.	288
	<i>Modiolus auriculatus</i> Krauss, 1848)	173
Pteriidae	<i>Pinctada</i> cf <i>margaritifera</i> (Linnaeus, 1758)	38
Isognomonidae	<i>Isognomon isognomon</i> (Linnaeus, 1758)	1
Spondylidae	<i>Spondylus</i> sp.	2
Ostreidae	Oysters rock	19
	Oyster flat 1	12
	Oyster flat 2	1
	Oyster sp.	1
HETERODONTA		
Chamidae	<i>Chama</i> sp.	10
Carditidae	<i>Cardita variegata</i> Bruguiere, 1792)	15
Tridacnidae	<i>Tridacna maxima</i> (Roding, 1798)	726
Veneridae	<i>Irus irus</i> (Linnaeus, 1758)	4
UNKNOWN		
	Clam red mantle	1

Chitons

Taxon	Species	Number
Chitonidae	<i>Acanthopleura gemmata</i> (Blainville, 1825)	97
	<i>Clavarizona hirtosa</i> (Blainville, 1825)	55
	Chiton smooth girdle	34
Cryptoplacidae	<i>Cryptoplax</i> sp.	3
	Chiton smooth	17
	Chiton 114	5
	Chiton pale	3
	Chiton white	3
	Chitons light	3
	Chitons - spinose tufts	1

Crustaceans * Hermit crabs were scored as present or absent in quadrats

Taxon	Species	Number
Cirrepedia	Barnacle 3 (acorn)	132
	Barnacle	43
	Barnacle 1	42
	Barnacle 2 (surf)	22
	Barnacle conical fine long ribs	20
Stomatopoda	<i>Squilla</i> sp.	1
Paguridae	Hermits	698*
Calappidae	<i>Calappa</i> sp.	2
Majidae	Crab camouflage	2
	Crab majid Nov08	2
	Crab majid Sep09	1
Portunidae	Crab smooth blu/black- portunid	8
	Crab pale cf portunid	5
Xanthidae	<i>Macromedalus</i> cf <i>crassimanus</i>	41
	Xanthid striped	2
Pilumnidae	Crab furry)	19
Grapsidae	Crab grapsid	1
	Crab blue-brown hairs on chelae	3
	Crab black clawed	2
	Crab cf smooth	2
	Crab smooth	2
	Crab hairy spotted legs	1
	Crab rough grey marbled	1
	Crab small brown	1
	Crab big brown	1

Gastropods * These two species are both recorded from Ningaloo Reef, but are difficult to distinguish, and we were not consistent in our identifications.

Family/Subfamily	Species	Number
DOCOGLOSSA		
Acmaeidae	<i>Patelloida</i> sp.	20
	<i>Patelloida alticostata</i> (Angas, 1865)	1
Patellidae	<i>Cellana</i> cf <i>radiata</i>	125
	<i>Scutellastra laticostata</i> (Blainville, 1825)	2
NERITMORPHA		
Neritidae	<i>Nerita undata</i> Linnaeus, 1758	345
	<i>Nerita albicilla</i> Linnaeus, 1758	268
ARCHAEOGASTROPODA		
Fissurellidae	<i>Macroschisma munita</i> Iredale, 1940	3
Haliotidae	<i>Haliotis varia</i> Linnaeus, 1758	23
Trochidae	<i>Tectus pyramis</i> (Born, 1778)	211
	<i>Tectus</i> cf <i>fenestratus</i> (Gmelin, 1791)	81
	<i>Angaria tyria</i> (Reeve, 1843) and or *	16
	<i>Angaria delphinus</i> (Linnaeus, 1758)	
	<i>Calothalotia</i> cf <i>strigata</i> (Adams, 1853)	4
	<i>Trochus hanleyanus</i> Reeve, 1842	3
	<i>Austrocochlea zeus</i> (Fischer, 1874)	1
Stomatellidae	<i>Pseudostomatella papyracea</i> (Gmelin, 1791)	1
	<i>Stomatella</i> sp.	1
Turbinidae	<i>Turbo haynesi</i> Preston, 1914	268
Phasianellidae	<i>Phasianella variegata</i> Lamarck, 1822	2
Liotiinae	<i>Liotina peronii</i> (Kiener, 1839)	20
NEOTAENIOGLOSSA		
Cerithiidae	<i>Clypeomorus batillariaeformis</i> Habe & Kosuge, 1966	2964
	<i>Rhinoclavis echinatum</i> Lamarck, 1822	468
	<i>Cerithium zonatum</i> (Wood, 1828)	421
	<i>Cerithium</i> cf <i>tenellum</i> Sowerby, 1855	357
	<i>Cerithium atromarginatum</i> Dautzenberg & Bruce 1933	13
	<i>Cerithium columna</i> Sowerby, 1834	13
	<i>Rhinoclavis bituberculata</i> (Sowerby, 1865)	12
	<i>Pseudovertagus aluco</i> (Linnaeus, 1758)	11
	<i>Cerithium</i> cf <i>nesioticum</i> Pilsbry & Vanetta, 1906	4
	<i>Clypeomorus bifasciata</i> (Sowerby, 1855)	1
	<i>Rhinoclavis brettinghami</i> Cernohoresky, 1974	1
	Planaxidae	<i>Planaxis sulcatus</i> (Born, 1780)
Modulidae	<i>Modulus tectum</i> (Gmelin, 1791)	2
Architectonicidae	<i>Ethminolia</i> cf <i>sundial</i>	1

Strombidae	<i>Strombus mutabilis</i> Swainson, 1821	2313	
Vermetidae	<i>Serpulorbis</i> cf <i>sipho</i>	2918	
Vermetidae	Vermetid ridged shell	11	
Cypraeidae	<i>Cypraea moneta</i> Linnaeus, 1758	201	
	<i>Cypraea caputserpentis</i> Linnaeus, 1758	132	
	<i>Cypraea helvola</i> Linnaeus, 1758	5	
	<i>Cypraea vitellus</i> Linnaeus, 1758	4	
	<i>Cypraea clandestina</i> Linnaeus, 1767	3	
	<i>Cypraea erronea</i> Linnaeus, 1758	3	
	<i>Cypraea lynx</i> Linnaeus, 1758	2	
	<i>Cypraea hirundo</i> Linnaeus, 1758	1	
	<i>Cypraea annulus</i> Linnaeus, 1758	1	
	<i>Cypraea kieneri</i> Hidalgo, 1906	1	
	<i>Cypraea limacina</i> Lamarck, 1810	1	
Triviidae	<i>Trivia</i> sp.	5	
Naticidae	<i>Natica euzona</i> Rècluz, 1844	2	
Bursidae	<i>Bursa granularis</i> (Röding, 1798)	2	
	<i>Bursa rosa</i> (Perry, 1811)	1	
Ranellidae	<i>Cymatium muricinum</i> (Röding, 1798)	19	
	<i>Cymatium nicobaricum</i> (Röding, 1798)	13	
	<i>Cymatium mundum</i> (Gould, 1848)	6	
NEOGASTROPODA			
Muricidae	<i>Cronia avellana</i> (Reeve, 1846)	1381	
	<i>Cronia crassulnata</i> (Hedley, 1914)	88	
	<i>Pascula ochrostoma</i> (Blainville, 1832)	61	
	<i>Drupa ricinus</i> (Linnaeus, 1758)	5	
	<i>Drupella cornus</i> (Röding, 1798)	3	
	<i>Drupina lobata</i> (Blainville, 1832)	2	
	<i>Morula</i> cf <i>uva</i> (Röding, 1798)	206	
	<i>Thais orbita</i> (Gmelin, 1791)	79	
	<i>Morula granulata</i> (Duclos, 1832)	32	
	<i>Thais aculeata</i> (Deshayes & Milne Edwards, 1844)	19	
	<i>Morula margariticola</i>	5	
	<i>Nassa francolina</i> (Bruguiere, 1789)	5	
	<i>Morula whiteheadae</i>	5	
	<i>Favartia salmonea</i> (Melvill & Standen, 1899)	3	
	<i>Thais alouina</i> Röding, 1798	3	
	<i>Morula nodicostata</i> (Pease, 1868)	2	
	<i>Pinaxia versicolor</i> (Gray, 1839)	1	
	Thaid 2	1	
	Coralliophilinae	<i>Coralliophila neritoidae</i> (Lamarck, 1816)	4
		<i>Coralliopila</i> cf <i>confusa erosa</i>	1
Buccinidae	<i>Cantharus erythrostomus</i> (Reeve, 1846)	5	

	<i>Crassicanthurus noumeensis</i> (Crosse, 1870)	3
Fascioliariinae	<i>Peristernia incarnata</i> (Kiener, 1830)	12
Nassariinae	<i>Nassarius reeveanus</i> (Dunker, 1847)	28
	<i>Nassarius sufflatus</i> (Gould, 1860)	2
	<i>Hebra horrida</i> (Dunker, 1847)	1
	<i>Nassarius albescens</i> (Dunker, 1846)	1
Columbellidae	<i>Pyrene turturina</i> (Lamarck, 1822)	80
	<i>Pyrene bidentata</i> (Menke, 1843)	66
	<i>Pyrene testudinaria</i> (Link, 1807)	51
	<i>Pyrene flava</i> (Brug, 1789)	37
	<i>Mitrella albina</i> (Kiener, 1841)	4
Costellariidae	<i>Vexillum cadaverosum</i> (Reeve, 1844)	9
Mitridae	<i>Mitra scutulata</i> (Gemin, 1791)	58
	<i>Mitra fraga</i> Quoy and Gaimard, 1833	3
	<i>Mitra puncticulata</i> Lamarck, 1811	1
	cf <i>Vexillum leucodesmum</i> (Reeve, 1845)	1
Turridae	<i>Turridrupa</i> sp.	17
Conidae	<i>Conus sponsalis</i> Hwass in Bruguiere, 1792	761
	<i>Conus dorreensis</i> Peron, 1807	117
	<i>Conus lividis</i> Hwass in Bruguiere, 1792	32
	<i>Conus chaldaeus</i> (Röding, 1798)	6
	<i>Conus coronatus</i> Gmelin, 1791	4
	<i>Conus ebraeus</i> Linnaeus, 1758	2
	<i>Conus lischkeanus</i> (Weinkauff, 1875)	1
Terebridae	<i>Terebra felina</i> (Dillwyn, 1817)	1
OPISTHOBRANCHIA		
Aplysiidae	<i>Aplysia dactylomela</i> Rang, 1828	6
	<i>Aplysia oculifera</i> Adams and Reeve, 1850	3
	<i>Aplysia parvula</i> Mörch, 1863	2
Vollvatellidae	<i>Volvatella</i> sp.	23
PULMONATA		
Siphonariidae	<i>Siphonaria</i> sp. 0	1373
	<i>Siphonaria</i> sp. 1	35
	<i>Siphonaria</i> sp. 2	23

Echinoderms

Taxon	Species	Number
Asteroidea	<i>Centrostephanus</i> sp.	21
	cf <i>Aquilomastra cepheus</i> (Muller and Troschel, 1842)	6
	<i>Astropecten</i> sp.	1
	<i>Nardoa</i> sp.	1
Crinoidea	cf <i>Comatula purpurea</i>	2
Echinoidea	<i>Echinometra mathaei</i> (Blainville, 1825)	1320
	<i>Stomopneustes</i> sp.	41
	<i>Peronella orbicularis</i> (Leske, 1778)	24
	<i>Nudechinus darnleyensis</i> (Tenison Woods, 1878)	19
	Echinoidea thin spines	4
	<i>Tripneustes</i> ?	2
	<i>Tripneustes gratilla</i> Linnaeus, 1758	2
Holothuroidea	<i>Holothuria atra</i> Jaeger, 1833	34
	<i>Holothuria</i> not atra	31
	Holothurian brown	5
	Holothurian white	1
	Holothurian black 1	1
	Holothurian black 2	1
	Holothurian black shiny	1
	Holothurian black stubby	1
	Holothurian black/red nodules	1
	Holothurian small brown	1
	Holothurian white spots	1
	<i>Leptosynapta</i> sp.	1
Ophuroidea	Ophiuroid large brown	16
	Ophiuroid fine thin armed	6
	Ophiuroid thin smooth stiff arms Ophiuridae	1

Other phyla

Taxon	Label	Number
Echirua	Echiuran large	1
Enteropneusta	Balanoglossus	8
Nemertea	Nemertean green	2
Cephalopoda	Octopus blue ringed	1
	Octopus sp.	2
	Squid dumpling	1
Porifera	Sponge brown	1
	Sponge	2

Jurabi February 2010 additional species in 452 1-m² quadrats

Group	Species	Number
Porifera	Sponge grey	13
	Sponge purple bag 155	5
	Sponge black	2
	Sponge white tubular	1
	Sponge encrusting green	1
Polychaete	Polychaete sedentary	13
	Polychaete errant	7
Bivalve	Mussel white <i>Veneropsis?</i> Bag 154	1
Chiton	Chiton granular girdle	2
	Chiton white spike bag 165	1
Actinaria	Anemone commensal <i>Tonna</i> /hermit	2
Alcyonacea	Soft coral JP photo bag 145	3
	Soft coral mustard	2
	Soft coral cream bag 151	2
Scleractinia	Coral 152	1
	Coral brown digitate	1
Zoanthidea	Zoanthid 142	3
	<i>Palythoa heideri</i> (Carlgren, 1954)	1
	Zoanthid fluorescent green	1
Calappidae	Crab calappidae	2
Majidae	Crab majid	8
Portunidae	Crab portunid	10
Xanthidae	Crab xanthid	7
Asteroidea	Starfish unidentified	3
Holothuroidea	Holothurian brown	39
	Holothuria small cream bag 137	3
	Holothurian thin epidermis	1
Ophuroidea	Ophiuroid	24
Strombidae	<i>Lambis chiragra</i> (Linnaeus, 1758)	1
Capulidae	<i>Capulus sp.</i>	1
Lamellariidae	Lamellariidae grey cream	1
Naticidae	<i>Polinices melanostomus</i> (Gmelin, 1791)	2
Naticidae	<i>Polinices cf sebae/simiae</i>	1
Bursidae	<i>Bursa bufonia</i> (Gmelin, 1791)	2
Tonnidae	<i>Tonna perdix</i> (Linnaeus, 1758)	1
Epitoniidae	<i>Epitonium cf fasciatum</i> (Sowerby, 1844)	1
Muricidae	<i>Morula square</i>	1
	<i>Drupa morum</i> Röding, 1798	1
	<i>Maculotriton cf serriale</i> (Deshayes, 1830)	1
Mitridae	<i>Mitra litterata</i> Lamarck, 1811	1
Pyramidellidae	Pyramidellidae?	2
Opisthobranch	Nudibranch all black	2

Nemertea	Nemertean white red stripe	2
	Nemertean cream	1
Echiura	Echiuran 148	1
Urochordate	Ascidian colonial	3
	Ascidian simple	1

Table 2. Occurrences of species of invertebrates on intertidal rocky platforms in the northern, central, and southern regions of Ningaloo Marine Park in 2007 and 2009. The entries on the diagonal of the two x two part of the table show the number of unique species, and the off diagonals the number of species shared by both of regions. The entries in parentheses are the tallies omitting singleton species. There were 24 species in the North that were unique to the 180 1-m² quadrats in 2008, and not included in the tallies here.

	Number of species in 2007		Total number of species
	North 10 sites	South 8 sites	
North	45 (20)		117 (71)
South	43 (38)	29 (13)	

	Number of species in 2009		Total number of species
	North 17 sites	South 16 sites	
North	19 (4)		187 (112)
South	53 (39)	115 (69)	

	Number of species in 2007 and 2009		Total number of species
	North 595 1-m ² quadrats	South 517 1-m ² quadrats	
North	67 (38)		219 (133)
South	70 (54)	82 (41)	

	Number of species		Total number of species
	2007 452 1-m ² quadrats	2009 660 1-m ² quadrats	
2007	32 (14)		219 (121)
2009	85 (57)	102 (50)	

Table 3. Distribution of identified species on intertidal platforms in Ningaloo Marine Park. The recorded distributions came from Australian Fauna Directory (Website, and other links), Lamprell and Healy (1992, 1998) [L&H 1, L&H 2, species code], Wells and Bryce (1985) [W&B Seashells, species code], Wells and Bryce (1993) [W&B Sea Slugs, species code], and Wilson (1994) [W1, W2, page number],

Species in North and South parts of Ningaloo Marine Park	Recorded distribution
	NINGALOO ONLY?
<i>Drupina lobata</i> (Blainville, 1832) Jul09)	Indian Ocean; Ningaloo Reef, WA W2, 43
	NORTHERN
<i>Cerithium atromarginatum</i> Dautzenberg & Bruce 1933)	North West Cape to Caloundra, Qld W1, 116
<i>Conus coronatus</i> Gmelin, 1791)	Point Cloates to northern NSW, W2, 204
<i>Conus sponsalis</i> Hwass in Bruguiere, 1792)	Rowley Shoals to Sydney NSW W2, 215
<i>Cronia crassulnata</i> (Hedley, 1914)	North West Cape to Gulf of Carpentaria W2, 22
<i>Holothuria atra</i> Jaeger, 1833	Kalbarri to north NSW AFD
<i>Modiolus auriculatus</i> Krauss, 1848	northern WA to GBR Islands L&H 2, 82
<i>Nudechinus darnleyensis</i> (Tenison Woods, 1878)	CSIRO data base
<i>Pascula ochrostoma</i> (Blainville, 1832)	Ningaloo Marine Park to central Qld W2, 24
<i>Peronella orbicularis</i> (Leske, 1778)	Bluff Point to Capricorn Group, Qld. AFD
<i>Vexillum cadaverosum</i> (Reeve, 1844)	Scott Reef to northern NSW W2, 163
	SOUTHERN
<i>Serpulorbis cf sipho</i>	southern Australia for <i>sipho</i> W1, 171
<i>Morula whiteheadae</i>	Rottnest, Shark Bay, Abrolhos (A. Brearley, pers. comm.)
	TO SOUTH AND NORTH
<i>Brachidontes ustulatus</i> (Lamarck, 1819)	South Australia to Kimberley W&B Seashells 556
<i>Cellana cf radiata</i>	Geraldton to Queensland W1, 36
<i>Cerithium cf nesioticum</i> Pilsbry & Vanetta, 1906	Cape Naturaliste to Caloundra, Qld W1, 117
<i>Cerithium cf tenellum</i> Sowerby, 1855)	Abrolhos Islands to Bunker Group, Qld W1, 119
<i>Cerithium zonatum</i> (Wood, 1828)	Shark Bay to Capricorn Group, Qld W1, 119
<i>Clypeomorus batillariaeformis</i> Habe & Kosuge, 1966)	Shark Bay to Moreton Bay, Qld W1, 120
<i>Conus chaldaeus</i> (Röding, 1798)	Abrolhos Islands to northern NSW, Qld W2, 202
<i>Conus dorreensis</i> Peron, 1807	Albany to Dampier W2, 204
<i>Conus lividis</i> Hwass in Bruguiere, 1792)	Rottnest Island to northern NSW W2, 209
<i>Cronia avellana</i> (Reeve, 1846)	Cheyne Beach to Kimberley W2, 22
<i>Cymatium muricinum</i> (Röding, 1798)	Shark Bay to eastern Qld W1, 244
<i>Cymatium nicobaricum</i> (Röding, 1798)	Rottnest Island to northern NSW W1, 246
<i>Cypraea caputserpentis</i> Linnaeus, 1758	Albany to southern NSW W1, 179
<i>Cypraea helvola</i> Linnaeus, 1758	Albany to northern NSW W1, 180

<i>Cypraea moneta</i> Linnaeus, 1758	Abrolhos to northern NSW W1, 184
<i>Drupa ricinus</i> (Linnaeus, 1758) Jul09)	Abrolhos Islands to Qld W2, 41
<i>Echinometra mathaei</i> (Blainville, 1825)	Indo Pacific
<i>Haliotis varia</i> Linnaeus, 1758	Abrolhos to southern Qld W1, 50
<i>Liotina peronii</i> (Kiener, 1839)	Fremantle to northern NSW W1, 101
<i>Mitra scutulata</i> (Gemin, 1791)	Cape Naturaliste to NSW W2, 152
<i>Mitrella albina</i> (Kiener, 1841)	Fremantle to Qld W2,104
<i>Morula cf uva</i> (Röding, 1798)	Abrolhos to northern NSW W2, 44
<i>Morula granulata</i> (Duclos, 1832)	Rottnest Island to Queensland W2, 44
<i>Nassarius reeveanus</i> (Dunker, 1847)	Abrolhos to Kimberley W2, 85
<i>Nerita albicilla</i> Linnaeus, 1758)	Shark Bay to northern NSW W1, 40
<i>Peristerna incarnata</i> (Kiener, 1830)	Geraldton to northern NSW W2, 73
<i>Phasianella variegata</i> Lamarck, 1822	Cheyne Beach to Dampier W1, 102
<i>Pinctada cf margaritifera</i> (Linnaeus, 1758)	Port Gregory to Qld W&B Seashells 156
<i>Pyrene testudinaria</i> (Link, 1807) Nov08)	Abrolhos Islands to northern NSW W2, 107
<i>Pyrene turturina</i> (Lamarck, 1822)	Abrolhos to southern Qld W2, 107
<i>Rhinoclavis bituberculata</i> (Sowerby, 1865)	Cape Leeuwin to southern Qld W1, 123
<i>Rhinoclavis echinatum</i> Lamarck, 1822	Rottnest to Capricorn Group Qld W1, 117
<i>Septifer bilocularis</i> (Linnaeus, 1758)	Rottnest to Queensland W&B Seashells 152
<i>Strombus mutabilis</i> Swainson, 1821	Cape Leeuwin to central NSW W1, 165
<i>Tectus cf fenestratus</i> (Gmelin, 1791)	Rottnest Island to southern Queensland W1, 89
<i>Tectus pyramis</i> (Born, 1778)	Rottnest Island to southern Qld W1, 89
<i>Tridacna maxima</i> (Röding, 1798)	Abrolhos to Qld W&B Seashells 168
<i>Trochus hanleyanus</i> Reeve, 1842 Jul09)	Abrolhos Islands to southern, Qld W1, 90
<i>Turbo haynesi</i> Preston 1914	Shark Bay to Hervey Bay Qld W1, 106

Species in the North part of the Park	Recorded distribution
	EASTERN
<i>Morula nodicostata</i> (Pease, 1868)	north Qld to northern NSW W2, 44
	NINGALOO ONLY ?
<i>Conus lischkeanus</i> (Weinkauff, 1875)	as <i>C. kermadecensis</i> W2, 208 (Indo-West Pacific)
<i>Crassicantharus noumeensis</i> (Crosse, 1870)	North West Cape W2, 67 (Indo-West Pacific)
	NORTHERN
<i>Angaria delphinus</i> (Linnaeus, 1758) [confused with <i>A. tyria</i>]	Exmouth Gulf to southern Qld W1, 96
<i>Bursa bufonia</i> (Gmelin, 1791)	Rowley Shoals and Scott Reef, WA to Qld. W1 226
<i>Cardita variegata</i> Bruguiere, 1792	north WA to central Queensland L&W 1, 162
<i>Cymatium mundum</i> (Gould, 1849)	Abrolhos to Qld W1, 245
<i>Cypraea hirundo</i> Linnaeus, 1758	Shark Bay WA to northern Qld W1, 176
<i>Cypraea kieneri</i> Hidalgo, 1906	North West Cape to north Qld W1, 176
<i>Drupa morum</i> Röding, 1798	Abrolhos to Qld W2, 41
<i>Epitonium fasciatum</i> (Sowerby, 1844)	north Qld to Cairns W1 277
<i>Favartia salmonae</i> (Melvill & Standen, 1899)	Dampier, WA to Swain Reefs Qld. W2, 37
<i>Hebra horrida</i> (Dunker, 1847)	North West Cape to north Qld W2, 77
<i>Isognomon isognomon</i> (Linnaeus, 1758)	North West Cape to , Qld W&B Seashells 156
<i>Macromedaeus cf crassimanus</i>	northern WA to northern NSW J&M, 166
<i>Maculotriron cf serriale</i> (Deshayes, 1830)	Barrow Island and Scott Reef WA to central NSW. W2 23
<i>Mitra fraga</i> Quoy and Gaimard, 1833	North West Cape to Bunker Group, Qld W2, 149
<i>Mitra puncticulata</i> Lamarck , 1811	North West Cape to Michaelmas Cay Qld W2,149
<i>Nassarius albescens</i> (Dunker, 1846)	North West Cape to central Qld W2, 80
<i>Pinaxia versicolor</i> (Gray, 1839)	Barrow Island to central NSW W2, 46
<i>Pyrene flava</i> (Brug, 1789)	North West Cape to Qld W2, 106
<i>Terebra felina</i> (Dillwyn, 1817)	Pt Cloates, WA to Qld W2 225
<i>Thais aculeata</i> (Deshayes & Milne Edwards, 1844)	Pt. Cloates to Qld W2, 48
<i>Vexillum cf leucodesmum</i> (Reeve, 1845)	Dampier to north Qld W2,168
	SOUTHERN
<i>Angaria tyria</i> (Reeve, 1843) [confused with <i>A. tyria</i>]	Fremantle to North West Cape, W1, 96
	TO SOUTH AND NORTH
<i>Acanthopleura gemmata</i> (Blainville, 1825)	Shark Bay to Qld, W&B, 11
<i>Aplysia dactylomela</i> Rang, 1828	Albany to NSW W&B slugs 43
<i>Aplysia parvula</i> (Mörch, 1863)	all around Australis W&B slugs 43
<i>Bursa granularis</i> (Röding, 1798)	Rottnest Island to northern NSW, W1, 226
<i>Cantharus erythrostomus</i> (Reeve, 1846)	Abrolhos Islands to southern Qld, W2, 90
<i>Cerithium columna</i> Sowerby, 1834	Abrolhos Islands to Gladstone Qld, W1, 116
<i>Clypeomorus bifasciata</i> (Sowerby, 1855)	Geraltion to Morton Bay Qld, W1, 120
<i>Coralliophila neritoidae</i> (Lamarck, 1816)	Abrolhos to Capricorn Group Qld, W2, 18
<i>Cypraea annulus</i> Linnaeus, 1758	Rottnest Island to southern NSW, W1,184
<i>Cypraea clandestina</i> Linnaeus, 1767	Abrolhos Islands to central NSW, W1, 188
<i>Cypraea limacina</i> Lamarck, 1810	Cape Leeuwin to northern NSW W1, 191

<i>Cypraea lynx</i> Linnaeus, 1758	Abrolhos to northern NSW W1, 193
<i>Cypraea vitellus</i> Linnaeus, 1758)	Cape Leeuwin to central NSW W1, 183
<i>Macroschisma munita</i> Iredale, 1940	Albany to Port Hedland W1, 54
<i>Modulus tectum</i> (Gmelin, 1791)	Shark Bay to southern Qld W1, 129
<i>Nassa francolina</i> (Bruguiere, 1789)	Abrolhos to Broome W2, 46
<i>Nerita undata</i> Linnaeus, 1758	Geraltion to southern Qld W1, 41
<i>Planaxis sulcatus</i> (Born, 1780)	North West Cape to northern NSW W1, 131
<i>Pseudostomatella papyracea</i> (Gmelin, 1791)	Rottnest Island to southern Qld W1, 74
<i>Pseudovertagus aluco</i> (Linnaeus , 1758)	Shark Bay to Whitsunday Group Qld, W1, 122
<i>Tripneustes gratilla</i> Linnaeus, 1758	Cape Leeuwin to south NSW ADF

Species found in the South part of the Park	Recorded distribution
	EASTERN
<i>Morula margaritica</i>	eastern Australia south to Sydney, W2, 44
	NORTHERN
<i>Bursa rosa</i> (Perry, 1811)	North West Cape to northern NSW W1, 227
<i>Calothalotia cf strigata</i> (Adams, 1853)	Exmouth Gulf to north Kimberly W1, 82
<i>Coralliopila cf confusa erosa</i>	Port Hedland, to Rowley Shoals to north Qld W2, 17
<i>Irus irus</i> (Linnaeus, 1758)	Northern WA to north Queensland, L&W 1, 597
<i>Natica euzona</i> Rècluz, 1844	Dampier to Sydney W1, 215/6
<i>Palythoa densa</i> Calgren, 1954	Australian some web site
<i>Rhinoclavis brettinghami</i> Cernohoresky, 1974	Barrow Island to Capricorn Group Queensland W1, 123
	SOUTHERN
<i>Clavarizona hirtosa</i> (Blainville, 1825)	Southern WA http://home.inreach.com/burghart/austral.html
<i>Palythoa heideri</i> (Calgren, 1954)	south and west WA ñ some web site
<i>Pyrene bidentata</i> (Menke, 1843)	South Australia to North West Cape W2, 106
<i>Scutellastra laticostata</i> (Blainville, 1825)	Esperance to Shark Bay W1, 37
<i>Thais orbita</i> (Gmelin, 1791)	southern to NW Cape, W2, 48
<i>Zoanthus marshi</i> Calgren, 1954	Rottneest to Kalbarri OBIS
	TO SOUTH AND NORTH
<i>Aplysia occulifera</i> Adams and Reeve, 1850	Cottesloe to Barrow Island W&B Sea Slugs, 40
<i>Austrocochlea zeus</i> (Fischer, 1874)	Cockburn Sound to Dampier Archipelago W1, 76
<i>Conus ebraeus</i> Linnaeus, 1758	Abrolhos to northern NSW, W2, 205
<i>Cypraea erroneus</i> Linnaeus, 1758	Shark Bay to northern NSW, W1, 181
<i>Drupella cornus</i> (Röding, 1798)	Abrolhos to Capricorn Group, Qld, W2, 42
<i>Isaurus tuberculatus</i> Gray, 1828	Rottneest to southern Qld. OBIS
<i>Nassarius sufflatus</i> (Gould, 1860)	Geralton to Barrow I, W2, 85
<i>Patelloida alticostata</i> (Angas, 1865)	northern NSW to Kalbarri W1, 33
<i>Pocillopora damicornis</i> (Linnaeus, 1758)	Indo Pacific
<i>Stomopneustes</i>	WA QLD AFD
<i>Thais alouina</i> Röding, 1798	Shark Bay to northern NSW, W2, 48

Table 4. Alpha, Beta, and Gamma diversity as Numbers Equivalents, according to Jost, L. (2007) as implemented by Charney and Record (2009) in the R package “vegetarian”, and rarefied number of species in a collection of 1000 individuals according to Heck *et al.* (1975) and Hurlbert, S.H. (1971) as implemented in function “rarefy” in the R package “vegan”(Oksanen *et al.* 2010) .

	Numbers equivalents \pm s.e			Number of individuals \pm se	
	${}^1D_{\alpha}$	${}^1D_{\beta}$	${}^1D_{\gamma}$	S	Number of species expected in 1000
2007					
Sites within Regions					
North (10 sites)	9.09 \pm 0.21	2.34 \pm 0.05	21.35 \pm 0.55	88	59.8 \pm 3.40
South (8 sites)	4.17 \pm 0.08	3.83 \pm 0.05	15.96 \pm 0.31	72	42.9 \pm 2.67
Regions within Ningaloo					
Ningaloo (2 regions)	12.51 \pm 0.15	1.41 \pm 0.01	17.60 \pm 0.25	117	
2009					
Sites within Regions					
North (17 sites)	8.00 \pm 0.15	2.82 \pm 0.05	22.52 \pm 0.48	111	42.00 \pm 3.05
South (16 sites)	5.42 \pm 0.08	3.83 \pm 0.04	20.77 \pm 0.33	125	77.09 \pm 4.38
Regions within Ningaloo					
Ningaloo (2 regions)	14.66 \pm 0.19	1.40 \pm 0.01	20.61 \pm 0.24	187	

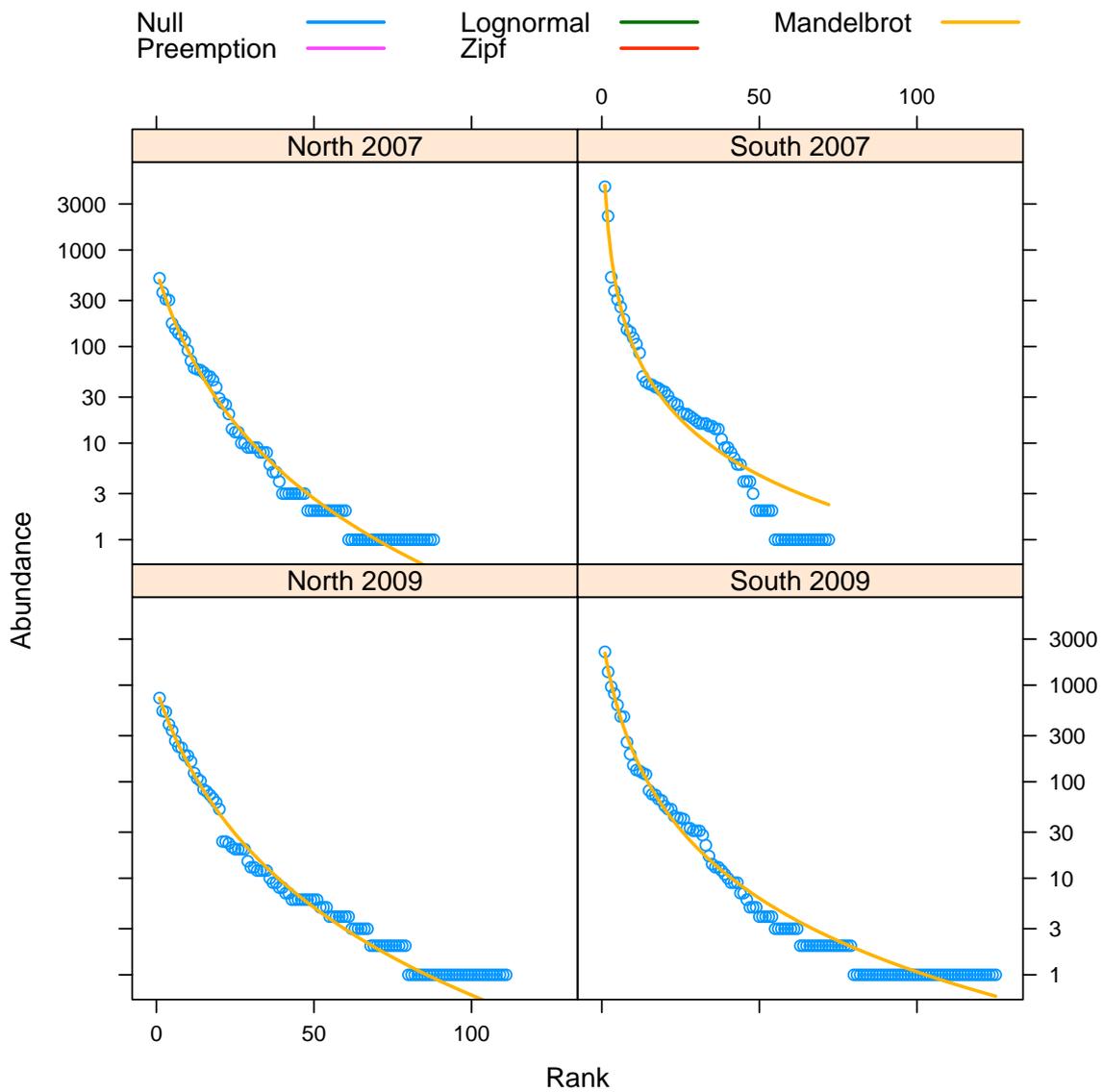


Figure 1. Rank-Abundance Dominance curves for the species found in Ningaloo Marine Park in 10 sites in the North and 8 sites in the South parts of the Park in 2007 and 17 sites in the North and 16 sites in the South parts of the Park in 2009. The Y-axis, Abundance is in a logarithmic scale. All four samples are best fit by the Mandelbrot model, but most noteworthy feature of these plots is the large number of species represented by one individual.

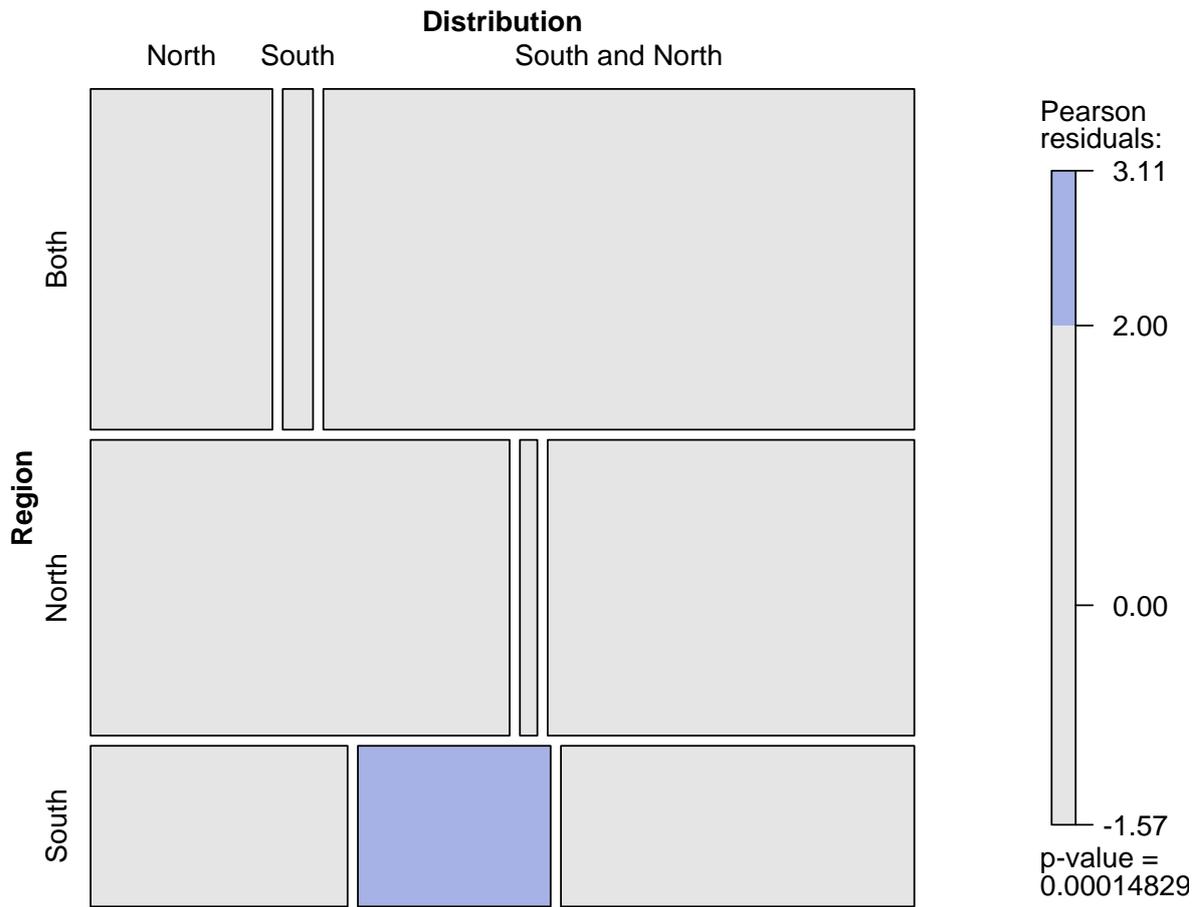


Figure 2. Mosaic plot of the recorded distribution of species at Ningaloo Marine Park which occurred in both, or one or the other of the north and south parts of the park (frequencies from details in Table 3). The blue rectangle represents an excess of species with a southern distribution among species found only in the south part of the park (Permutational contingency test, $p < 0.001$).

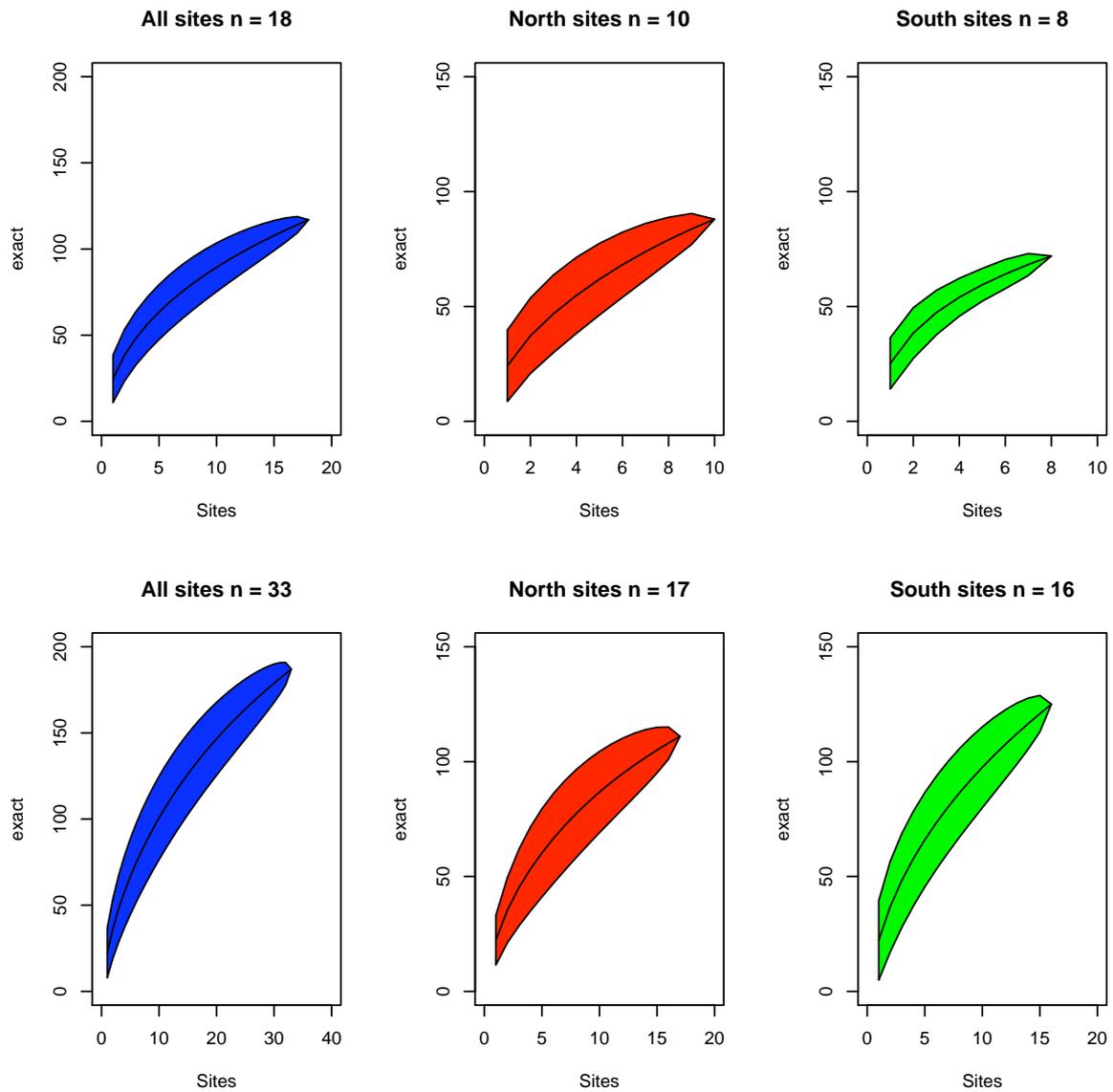


Figure 3. Sample-based species accumulation curves \pm standard deviations for invertebrates on intertidal platforms at sites in the Ningaloo Marine Park in 2007 top row, and 2009 bottom row. The panels have different scales on vertical and horizontal axes. Calculations were according to function “specaccum” using the “exact” method, in package “vegan” (Oksanen *et al.* 2010).

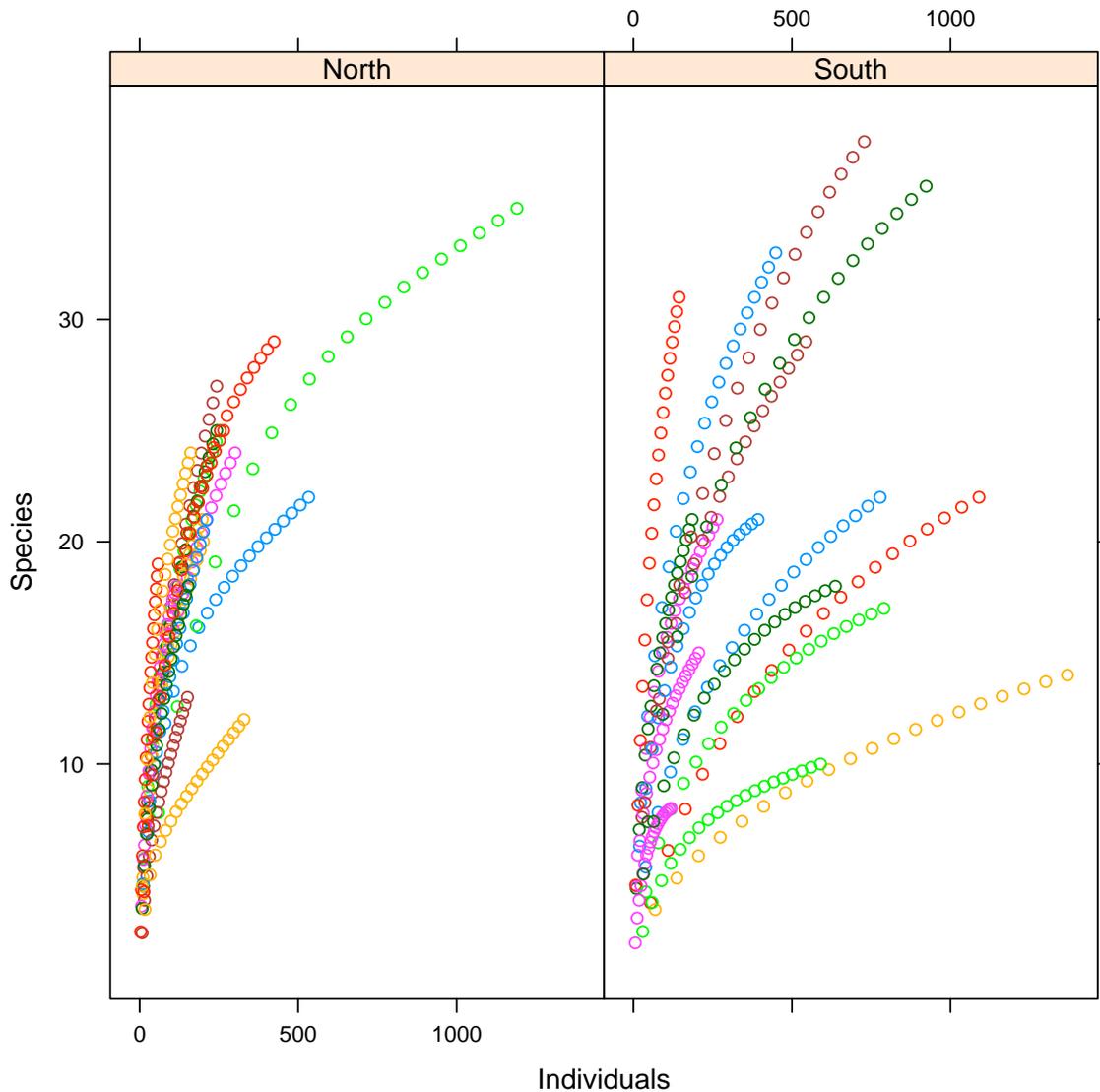


Figure 3. Individual-based species accumulation curves for each site in the North and South of Ningaloo Marine Park in 2009. Each curve is for a site and has twenty points representing the 20 quadrats taken at each site. The right end of each curve shows the sum of number of individuals in the sample of 20 quadrats (X axis) and the number of species (Y axis) in the 20 quadrats. The steeper the rise of the curve, the more evenly the species are distributed among species.

Chapter 3: Cowries on rocky intertidal platforms at Ningaloo Marine Park



Cypraea caputserpentis - photo by Alan Kendrick



Cypraea moneta - photo by Anne Brearley



Addie Bevilaqua at Surfers South - photo by Robert Black

Introduction

Cowries have attracted intense attention from taxonomists and shell-collectors because of their diversity and their colourful, glossy shells. Cowries are in the gastropod family Cypraeidae, are wide-spread in the Indo West Pacific, and typically live in warm waters. Australia has 77 species (Beesley *et al.* 1998). However, far less is known about their ecology and demography than would be expected based on the focus on their taxonomy, and in comparison with other intertidal gastropods (Prince 1992). Our standard quadrat sampling of 1292 m² in the central part of rocky intertidal platforms in Ningaloo Marine Park included cowries among the 243 kinds of organisms. Even the most abundant species of cowry, however, was represented by only 201 individuals, 23rd most abundant. This chapter provides an account about the cowries found in our quadrat sampling, and about other sampling designed to reveal more about their distribution and abundance on the rocky intertidal platforms.

Methods

We counted cowries in 1-m² quadrats in our standard sampling of usually 20 quadrats per site in August 2007, November 2008, and July and September 2009. Chapter xx provides details of the methods, the sites, and the rationale for the design of sampling. In this chapter, we use the data on cowries to describe the occurrence of these species, and for the two most abundant species to examine spatial and temporal variability in abundance and their association with each other. We also conducted two intensive studies to examine microhabitats used by these two species. These were carried out by Adelaide May Bevilaqua as part of a Fourth Year Research Project at the University of Western Australia.

The first intensive study involved sampling with 0.25-m² quadrats in nearby sections of the platforms where cowries were abundant or absent, to determine the characteristics of the substratum within the quadrats that might favour cowries. This was done at sites in the northern part of Ningaloo Marine Park, in February and July 2009. A second, larger

sampling scheme involved belt transects inshore from our standard mid-platform location because cowries appeared to be more abundant closer to shore. One belt transect, usually 60 m long and 3 m wide, was parallel to shore. Three shorter belt transects, 15 m apart and perpendicular to and seaward from the first transect, were 20 m x 3 m, although the number and length varied at some sites. We searched the belt transects carefully for cowries, and noted the microhabitat where each was found. The occurrence of various microhabitats was scored in a series of 30 0.25-m² quadrats regularly spaced along the parallel belt transect, and 21 0.25-m² quadrats along each of the perpendicular belt transects.

In intense sampling in February 2010, we focused on the northern boundary of the Jurabi Sanctuary Zone, sampling the five sites already established there and three others, so that there were four sites inside the sanctuary, and four sites outside. An earlier power analysis of the ability to detect two-fold differences in number of species per site or in abundance of selected species between inside and outside sanctuary zones had suggested that four replicate sites for each condition were required (Chapter yy). Here we tested this test this idea for the abundance of cowries.

At each site, we sampled two sets of 25 1-m² quadrats in our standard way, counting all the macroinvertebrates in each quadrat. One set of quadrats was at random locations within a defined area, and one set was in a regular 5 by 5 grid to ensure that all parts of the defined area were sampled. There were no differences in the community of organisms between the random and grid samples, so we considered them replicates. Because the cowries were so rare in these samples, we used the sum of each species of cowry in 25 m² as the dependent variable. The design of our analysis was, therefore, two levels of the fixed factor Sanctuary, four levels of the random factor Site nested with levels of Sanctuary, and two replicate counts nested within each Site, for a total of 16 observations. We used the program G*Power, Macintosh PPC Version 2.1.1 (Erdfelder *et al.* 1996) to calculate *post hoc* power associated with the analyses of variance.

Results

Species

Eleven species of cowries were found in our sampling of replicate 1-m² quadrats in the central parts of rocky intertidal platforms attached to shore at sites along the length of Ningaloo Marine Park; all but two were rare in this habitat (Table 1). *Cypraea moneta* (money cowry, 3 cm) and *Cypraea caputserpentis* (serpent's head cowry, 3.5 cm) were by far the most abundant. The densities of all cowries, shown by Table 2, were essentially the sum of these two species, which were wide-spread throughout the Park, at sites from Surfers North in the north to Three Mile In 1 in the south. The seven sites where our sampling found no cowries included sites in the north and south of the park.

Changes in abundance over time

The quadrat sampling involved 35 sites sampled one to four times between August 2007 and February 2010. Figure 1 shows the abundances of *C. moneta* and *C. caputserpentis* at each site for the times each was sampled. The abundances were transformed by $\log_{10}(\text{Number m}^{-2} + 1)$ because most quadrats had no cowries. Also, the logarithmic transform makes the slopes of lines joining points represent rates of change. Parallel lines, no matter what elevation on the plots, represent equal rates of change, and straight lines joining three points indicate constant rates. For example, at Jurabi In 1 (Figure 1 a), *C. moneta* declined to zero at a steady rate over the three times, and at Bateman Bay In (Figure 1 c), both species declined in abundance at the same rate between the two dates.

Table 3 summarizes apparent changes in density of the two species, based on the criterion that two means with non-overlapping standard errors represent real differences in density. Judged in this way both species had instances of increases, decreases and no changes over time, and the relative frequencies of the changes were judged similar for both species by a contingency test. Furthermore, at the 14 sites where they co-occurred, there were three times when one of the species changed in two directions over the intervals. The species changed in different directions 10 times and in the same direction 7 times, although the two species

changed abundance independently as tested by a 3 x 3 contingency test -for levels increase, decrease, and remain the same (permutational $p = 0.879$).

A more quantitative and controlled view of changes in abundance is possible for the four sites sampled in August 2007, November 2008, and July 2009 in the northern part of the Park. A fifth site, Mildura Wreck, was also sampled at these times, but, as Table 1 shows, our sampling found no cowries there. In fact, the data for the four sites sampled three times suffer from a general difficulty for analyses of abundances of individual species, especially for those that are rare. In the 240 1-m² quadrats in this data set, there were 54 *C. moneta* but only 11 *C. caputserpentis*; 200 of the quadrats contained neither species, and only four had both. Figure 2a reflects this, in that the money cowry was slightly more abundant and more variable than the serpent's head cowry at these sites. The rank order of the sites by abundance differed between 2007 and 2009 for both species, and for *C. moneta* the abundances declined to low values between 2008 and 2009. Also, as judged by the criss-crossing of the lines between adjacent dates, the changes in abundances of both species varied independently by site. This feature is emphasized for both species by the formal analyses of variance in Table 4a, in which the Date x Site terms are statistically significant, and, for the serpent's head cowry, with the largest component of variance associated with the first of the three terms of the model. In some cases, one species increased when the other species declined at the same site. Table 4a also shows that the most variation was among replicate quadrats within the Date and Site combinations.

A comparable analysis was possible for six sites sampled twice in the southern part of the Park (Table 4-b and Figure 2-b). Unlike at the sites in the north, *C. caputserpentis* and *C. moneta* were equally abundant (75 and 78 respectively in 267 1-m² quadrats). *C. caputserpentis* differed among sites. The significant interaction between Site and Date for *C. moneta* was because one site (Gnarraloo Bay In 1) increased dramatically from 2007 to 2009, while all the others declined slightly. As in the north, the largest component of variance was due to differences among quadrats at the same site at the same time.

Detecting differences in abundance between inside and outside a sanctuary zone

The total number of cowries in the intense study of the central part of the rocky intertidal platforms at the northern boundary of Jurabi Sanctuary Zone in February 2011 was not large, with 19 *C. caputserpentis* and 31 *C. moneta*. Of the 400 1-m² quadrats 358 had no cowries, 1 had both species, 16 had only *C. caputserpentis*, and 25 only *C. moneta*, indicating that the two species of cowries occurred in the quadrats independently of each other (2 x 2 permutational contingency test, $p = 1.000$).

Analyses of variance showed that the abundance of neither species differed between inside and outside the sanctuary zone, although each species had a numerically larger mean outside the sanctuary zone by factors of 1.1 for *C. caputserpentis* and 1.4 for *C. moneta* (Table 5). Both analyses showed that most of the variation for the random factors was associated with the two replicate counts at each site as judged by the % variance component. There were statistical differences in abundance among sites only for *C. moneta*. Power to detect a two-fold difference in abundance between inside and outside the sanctuary zone, given the observed variation among sites, was 0.1131 or 0.3993. To achieve a power of about 0.80, 43 or 9 sites per level of sanctuary would be required for *C. caputserpentis* and *C. moneta* respectively. As the table shows, increasing the magnitude of the difference between means increases the power of the test and decreases the number of replicate sites per level of Sanctuary.

Occurrence of cowries on inshore portions of the intertidal platforms

Casual observations suggested that cowries might be more abundant in the part of the intertidal platforms inshore of where we sampled with 1-m² quadrats. Surveys of belt transects, covering much larger areas than the quadrat sampling, at six sites in the northern part of Ningaloo Marine Park confirmed this difference in some places, but not in others (Table 6a). One or the other species was absent from some sites. Both species were on the inshore part of the platform at Mildura Wreck, whereas the quadrat sampling never found

cowries on central part of the platform. In contrast, the inshore parts of the platform at Surfers South and Jurabi Out 1 lacked one of the species, but both occurred on the central part of the platforms.

The samples from the belt transects provided much larger numbers of cowries than the quadrat sampling, but numbers were highly variable. Although *C. caputserpentis* appeared to be more abundant closer to shore in the parallel transects than farther from shore in the perpendicular transects, with the reverse pattern for *C. moneta* (Table 6-a), this was not supported by an analysis of variance (Table 6b).

Association of C. caputserpentis and C. moneta with each other; and features of their habitat

C. moneta and *C. caputserpentis* occurred together at 18 sites, and each occurred at five additional sites without the other (Table 7-a, which includes samples from sites at Jurabi in 2010). The contingency test suggested that this is a statistically significant association at the spatial scale of sites, so the habitat of the central parts of the intertidal platforms is appropriate for both species.

At the scale of the individual 1-m² quadrats used in our sampling, the pattern of association between these species is less clear because of the infrequent occurrence of cowries in the samples. Of the ten sites analyzed in Table 4, both species occurred together at six, and each occurred alone at two. Within each of the six sites, the two species occurred independently of each other, based on 2 x 2 contingency tables of with and without each species ($p = 0.08$ to 1.0 , permutations tests). Contingency tables for northern and southern sets of sites pooled across sites emphasized how rarely these cowries occurred in our 1-m² quadrats in the centre of the intertidal platforms (Table 7b).

The study of cowries living on the inshore parts of the platforms at six sites in the north part of the marine park provided details about the use of microhabitats. The 0.25-m² quadrats at

Mildura Wreck that were centered on randomly selected points in an area with cowries had less than half the number of crevices than quadrats centered on cowries, and about the same number of crevices as in an nearby area where cowries were absent (Figure 3). Crevices provide good microhabitats for *C. caputserpentis*, as judged too by the fact that random quadrats had about one-quarter the number of cowries as the cowry-centered quadrats.

However, as Table 8 shows, crevices were not the only microhabitat used by cowries on the inshore parts of the platforms. The 19 categories recorded indicate how diverse the surfaces of the platforms were. Overall, *C. caputserpentis* occurred most frequently on rocky substratum that was bare, in depressions and underneath rocks lying on the surface. *C. moneta* used bare rock most, like the other species, but also used shallow sand and algae in depressions. Three of the five sites where 2 x k permutational contingency tests were possible, showed significant heterogeneity in the microhabitats used by the two species. More than expected numbers of *C. moneta* were in algae in depressions and algal bound sand, and fewer than expected in loose rock/rubble in depressions, and underside of rock. *C. caputserpentis*, on the other hand, showed two instances of more than expected numbers in loose rock/rubble in depressions and one case on the underside of rocks. The contingency tests on the pooled numbers of each species in each microhabitat showed more instances of excess or deficit in numbers, but these should be considered with extreme caution because the availability of the microhabitats differed among sites.

There were consistent patterns in the estimated availability of microhabitats and density of cowries in the belt transects at six sites in the north of Ningaloo Marine Park. As judged by comparing the lightly shaded bars in Figures 4-a and 4b, the availability of nine categories of microhabitats varied considerably among the sites, and between the parallel and perpendicular transects, emphasizing the heterogeneity of the inshore parts of the platforms. Similarly, the pattern of use by the cowries varied among sites and between the two parts of the inshore platform. Importantly, because the pattern of relative density of cowries and relative frequency of microhabitat was drastically different in each of the 12 cases shown in Figure 4-a and b, the cowries occurred non-randomly with respect to the categories of microhabitats.

All the categories of microhabitat were occupied by cowries in at least one of the 12 combinations of site and type of transect, even categories C and D, which were judged to be exposed and perhaps unsuitable for them. The cowries occurred consistently, but at low densities, in categories E and F, which were judged to be protected and suitable for cowries. Cowries also occurred on the underside of rocks (category I) even when this microhabitat was so infrequent that its frequency was estimated as 0.0 (Figures 4-a and b).

Discussion

The assemblage of cowries on intertidal platforms

According to Wilson (1993), *C. caputserpentis* is “very common”, *C. moneta* is “one of the most common of all cowries”, and both live in the open, high in the rocky intertidal zone. Similarly, he explains that other species that we found in Ningaloo Marine Park on the rocky intertidal platforms range from “very abundant” to “moderately common” in tropical rocky intertidal habitats. *C. kieneri* is an exception by being “rather uncommon” and having its southern boundaries at North West Cape and northern Queensland, unlike all the others, which have southern boundaries between Albany and Shark Bay in Western Australia, and northern, central, or southern New South Wales. Thus, the species revealed by our survey of Ningaloo Marine Park are expected ones, with large tropical distribution in northern Australia.

Although *C. caputserpentis* and *C. moneta* are common, with a wide-spread geographic distributions, their densities at the sites and times of our surveys were low, rarely exceeding 1 m⁻² for both species combined (Tables 2 and 6). In a study that sampled 26 sites with 1-m² quadrats at Rottnest Island in 1990, mean densities were 0.05 to 0.60 m⁻² in eight sites where *C. caputserpentis* occurred, similar to densities in our study (Prince 1992, Table 4.4). However, *C. caputserpentis* could be locally very abundant in preferred habitat near the edge of the platforms, reaching 20 m⁻². (Prince 1992, Figure 4.6), an abundance that we never

observed at Ningaloo Marine Park. Irie (2006, Table 2) reported densities of *C. annulus* ranging from 0.42 to 12.72 m⁻² at four sites in Okinawa. It is difficult to know what Wilson's (1993) qualitative evaluations of abundance mean, but our quantitative data indicate that in most places on rocky intertidal platforms it would take tens of square meters of surface to yield ten cowries.

Demographic processes of C. caputserpentis and C. moneta

The cowries that we counted in all our surveys were adults. Prince's (1992) study of *C. caputserpentis* found recruits in November, which by April had almost all grown to be adults; a new cohort of recruits appeared the next November. Thus, if episodes of recruitment are similarly timed at Ningaloo Marine Park, we would not expect our surveys in August 2007; and July and September 2009 to find recruits or juveniles. Given the low density of cowries; and the cryptic behaviour of the recruits, it is unclear whether our surveys in November 2008 and February 2010 just failed to detect any recruits or juveniles, or if there actually were none. However, there is evidence that there must have been some recruitment between 2007 and 2009 in at least three populations of *C. moneta*, Surfers South, Mangrove Bay, and Gnarraloo Bay In 1, because the densities there were larger in 2009 (Figure 1). *C. caputserpentis* had no large increases in density, but five sites had similar densities between 2007 and 2009, as did *C. moneta*, indicating, at the very least, a balance between gains and losses to the populations over that interval. We have no direct estimates of the natural rate of mortality of adult cowries, or of their longevity, although *C. caputserpentis* marked as adults survived for two more years at Rottnest Island, Western Australia (J. Prince pers. comm. April 2011). Because *C. moneta* declined in abundance in five sites, mortality must have exceeded any gains by recruitment to those sites. In sum, based on the patterns of Figure 1, recruitment and mortality of cowries varied considerably among sites, especially for *C. moneta*, even over the short period of this study.

The independence of demographic processes among sites is also indicated by the analyses of variance, in which significant Date x Site interactions were a feature in three of the four tests

(Table 4-a and b). However, the small size of the component of variance indicates that its influence was not large. By far the most variability in density of both species of cowry in the two sets of analyses was associated with the variability among quadrats from each combination of Site and Date.

This huge among-quadrats variability is a consequence of the infrequent occurrence of the cowries in the 1-m² quadrats, an indication of a mis-match between abundance and size of quadrat, or an unusual spatial distribution of the cowries (unlikely). In fact, low abundance is a feature shared with most of the individual species found in the quadrat sampling that was designed primarily to sample the whole assemblage of species on the platforms. One remedy for this difficulty is to use larger sampling units, as we did in the focused study at Jurabi Sanctuary Zone in February 2010, where we pooled numbers of cowries in two sets of 25 1-m² quadrats.

Detecting differences inside and outside sanctuary zones

An answer to the question, “Does a specified sanctuary zone enhance the abundance of a particular species compared with abundance outside the zone?”, requires precise definitions of what is meant by “enhance”, and what is the basic experimental unit for the comparison. The basic, independent experimental units in this case are the units that we called sites; replicate sites inside and outside sanctuary zones are required to answer the question, and this dictated the design and analysis shown in Table 5 for cowries or any other dependent variable. The clear result was that the abundance of neither *C. caputserpentis* nor *C. moneta* differed on either side of the northern boundary of the Jurabi Sanctuary Zone, even with the four replicate sites for each condition. The tests had 1 and 6 df because the four replicated sites providing the independent sampling units for each level of Sanctuary each contributed 4-1 = 3 df. The two replicate sets of estimates of abundance at each site are not independent because they are nested within site, so their df do not contribute to the statistical test, but provide a more precise estimate of the mean.

Furthermore, the originally-posed question is incomplete in a very important aspect, especially in the context of failing to detect a difference, that is, accepting the formal null hypothesis of no difference in the statistical test. That aspect is, what does “enhance” mean, or in terms of hypotheses, what is the alternative to the null hypothesis? This is a definition that the investigator or manager must decide on when designing an experiment or monitoring programme. We made the arbitrary choice of wanting to be able to detect, at least, a rather large difference (two fold) between inside and outside the sanctuary zone. This would be means of 0.79 and 1.58 instead of 1.125 and 1.250 m⁻² for *C. caputserpentis* or 1.29 and 2.58 instead of 1.625 and 2.250 m⁻² for *C. moneta* (Table 5). Combining the alternative hypotheses for this effect-size with level of significance of the statistical test or Type I error rate, and an estimate of within-groups standard deviation, allows a calculation of the *post hoc* power of a statistical test. We used Type I error of $\alpha = 0.05$ (the probability of rejecting a null hypothesis when it is in fact true), and the observed estimate of standard deviation (square root of the mean square = Sigma) of the denominator for the F-test of the Sanctuary term (Site[Sanctuary]) from the analysis of variance.

Power is $(1 - \beta)$, so the power analysis essentially calculates β , where β = Type II error, the probability of accepting a null hypothesis when it is actually false. The values of α and β for powerful statistical tests are arbitrary, but there are two conventions. One is that α should equal β . This is a tough condition if $\alpha = 0.05$, and is sometimes eased by using 0.1 for both. Another is to aim for a power of 0.8, or $\beta = 0.2$. The *post hoc* powers of our comparisons to detect a two-fold difference in abundance of cowries inside and outside the Jurabi Sanctuary Zone in February 2010 were far from the conventional 0.80, at 0.1131 and 0.3993. Expressed in a different way, to achieve a power of 0.80, these comparisons would need many more replicate sites (43 or 9) than seems possible, either logistically, or from lack of suitable sites.

Of course, the underlying reason for the low power of these statistical analyses is out of control of the investigators. Variation among sites in the numbers of cowries (Sigma) was just too large. Sigma might be less at another time, or for another set of sites, but all the analyses of abundance of cowries at Ningaloo Marine Park indicated that there was considerable site-to-site and time-to-time variation. Because of this large natural variation,

detecting differences and changes of specified amounts will be difficult, requiring substantial replication of the appropriate experimental unit. If large Sigmas are unavoidable, with the consequence of low power to detect differences with reasonable amounts of replication, the only approach for researchers and managers to achieve powerful tests is to be reconciled to detecting nothing but huge differences, as indicated in Table 5 by the increase in power as the factor of difference between means increased.

Microhabitats used by cowries

Although Wilson's (1993) claim that *C. caputserpentis* and *C. moneta* live in the open in the rocky intertidal is certainly true, especially when they are foraging when it is dark, and in comparison to species that seek dark refuges during the day, these cowries are clearly associated with particular microhabitats. Crevices that provide walls and overhangs, rubble in depressions, and undersides of rocks are places used by *C. caputserpentis*. *C. moneta* occurs with sand and algae. Nevertheless, at all the scales of our sampling, from sites within the Ningaloo Marine Park, to individual belt transects, and 1-m² quadrats to microhabitats within those, the occurrence of an individual cowry probably depends on more factors than we considered, and it is difficult to specify characteristics of prime habitat that apply to all sites.

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Table 1. Cowries in the 1292 1-m² quadrats from sampling in 2007, 2008, and 2009 at Ningaloo Marine Park.

Species	2007 452 m ² 17 sites	2008 180 m ² 8 sites	2009 660 m ² 32 sites	Total
<i>Cypraea moneta</i> Linnaeus, 1758	76	49	76	201
<i>Cypraea caputserpentis</i> Linnaeus, 1758	54	6	72	132
<i>Cypraea helvola</i> Linnaeus, 1758	1		4	5
<i>Cypraea vitellus</i> Linnaeus, 1758		4		4
<i>Cypraea clandestina</i> Linnaeus, 1767	1		2	3
<i>Cypraea erronea</i> Linnaeus, 1758		1	2	3
<i>Cypraea limacina</i> Lamarck, 1810			1	2
<i>Cypraea lynx</i> Linnaeus, 1758		1	1	1
<i>Cypraea</i> 4 black spots Nov08		1		1
<i>Cypraea annulus</i> Linnaeus, 1758		1		1
<i>Cypraea kieneri</i> Hidalgo, 1906		1		1

Table 2. Density of cowries of all species at 33 sites in Ningaloo Marine Park sampled in 2007, 2008, and 2009. The sites marked with an * were sampled in each year.

Site	Number of 1-m ² quadrats	Sum of cowries, all species	Number m ⁻²
Gnarraloo Bay In 1	40	52	1.30
Gnarraloo Bay Out 2	20	21	1.05
Elles Out	20	13	0.65
Mangrove Bay*	80	44	0.55
Bateman Bay Out 2	20	11	0.55
Three Mile Out 1	40	21	0.53
Coral Bay South	49	25	0.51
Bateman Bay In	50	22	0.44
Jurabi Out 1*	60	25	0.42
Bateman Bay Out 1	51	20	0.39
Gnarraloo Bay Out 1	37	14	0.38
Jurabi In 2	40	15	0.38
Jurabi In 2/3	20	6	0.30
Jurabi In 3	20	5	0.25
Gnarraloo Bay In 2	20	4	0.20
Jurabi In 1*	60	11	0.18
Jurabi Out 2	40	6	0.15
Yardie Creek North	20	3	0.15
Mandu South Cobble	40	5	0.13
Mandu South Flat	40	5	0.13
Surfers South*	80	9	0.13
Mangrove Point	40	4	0.10
Surfers North	55	5	0.09
Pilgramunna	50	4	0.08
Three Mile In 1	40	2	0.05
Coral Bay North	50	2	0.04
Elles In	20	0	0
Mildura Wreck*	80	0	0
Mildura Wreck West	30	0	0
Three Mile In 2	20	0	0
Three Mile North	20	0	0
Three Mile Out 2	20	0	0
Yardie Creek South	20	0	0

Table 3. Changes in densities of *C. moneta* and *C. caputserpentis* at 20 sites in Ningaloo Marine Park visited two to four times, -August 2007- February 2010. The table contains records for both species at 20 sites with an additional four instances where one of the species experienced changes in both directions. Increases and decreases were judged by means $\log_{10}(\text{Number m}^{-2} + 1)$ with non-overlapping standard errors as seen in Figure 1. Permutational contingency test gave $p = 0.840$.

In the 14 sites with both species, they changed in the same way at 4 sites and in different ways at 10 sites (Goodness of fit test based on expectation of equality with Yate's correction gave $p = 0.1042$).

Condition	Number of site-occurrences		Total
	<i>Cypraea cauputserpentis</i>	<i>Cypraea moneta</i>	
Species absent	3	3	6
Decrease	6	9	15
Increase	7	5	12
No change	5	6	11
Total	21	23	44

Table 4. Analysis of variance of $\log_{10}(\text{Number } m^{-2} + 1)$ of two species of cowries at four sites censused by 20 1-m^{-2} quadrats on each of three dates (a), or six sites on two dates (b). Sites and Dates are considered random factors, so the main effects and interaction terms have variance components. Figure 2 -shows the least squares means and standard errors for the Date x Site term.

a. North

Cypraea moneta money cowry

Term	df	MS	F	p	Variance component as %
Date	2	0.1521	3.492	0.099	6.4
Site	3	0.0289	0.663	0.604	0.0
Date x Site	6	0.0436	2.324	0.034	5.8
Residual	228	0.0187			87.8
Total					100.0

Cypraea caputserpentis serpent's head cowry

Term	df	MS	F	p	Variance component as %
Date	2	0.0065	0.5668	0.595	0.0
Site	3	0.0061	0.5353	0.675	0.0
Date x Site	6	0.0114	2.5956	0.019	7.6
Residual	228	0.0044			92.4
Total					100.0

b. South

Cypraea moneta money cowry

Term	df	MS	F	p	Variance component as %
Date	1	0.01869	0.2165	0.6612	0.0
Site	5	0.44871	5.1580	0.0480	28.2
Date x Site	5	0.08699	4.6678	0.0004	10.7
Residual	255	0.01864			61.1
Total	266				100.0

Cypraea caputserpentis serpent's head cowry

Term	df	MS	F	p	Variance component as %
Date	1	0.00521	0.5544	0.4885	0.0
Site	5	0.10904	11.7791	0.0085	8.8
Date x Site	5	0.00926	0.3753	0.8654	0.0
Residual	255	0.02466			91.2
Total	266				100.0

Table 5. Analysis of numbers of *C. caputserpentis* and *C. moneta* at four sites inside and four sites outside the Jurabi Sanctuary Zone in February 2011. Each site had two sets of samples of 25 1-m² quadrats. Variance components are for the random factors

a. *C. caputserpentis*

Analysis of variance

Source	df	MS	F	p	Variance component as %
Sanctuary	1	0.06250	0.0545	0.8231	
Site[Sanctuary]	6	1.14583	0.6790	0.6723	0
Residual	8	1.68750			100

Post hoc Power analysis: Sigma = 1.2990

Sanctuary	Observed Mean ± s.e.	Alternative hypotheses about differences between means				
		Two-fold	Three-fold	Four-fold	Five-fold	Six-fold
In	1.2500 ± 0.3784	1.5833	1.7813	1.9000	1.9792	2.0357
Out	1.1250 ± 0.3784	0.7917	0.5938	0.4750	0.3958	0.3393
Power		0.1131	0.1945	0.2585	0.3068	0.3400
n for power = 0.80		43	20	14	12	10

b. *C. moneta*

Source	df	MS	F	p	Variance component as %
Sanctuary	1	1.5625	0.2852	0.6125	
Site[Sanctuary]	6	5.47917	6.7436	0.0084	74
Residual	8	0.81250			26

Post hoc Power analysis: Sigma = 0.9014

Sanctuary	Observed Mean ± s.e.	Alternative hypotheses about differences between means				
		Two-fold	Three-fold	Four-fold	Five-fold	Six-fold
In	2.2500 ± 0.8275	2.5833	2.9063	3.1000	3.2292	3.3214
Out	1.6250 ± 0.8275	1.2917	0.9688	0.7750	0.6458	0.5536
Power		0.3993	0.7177	0.8574	0.9154	0.9480
n for power = 0.80		9	5	4	4	4

Table 6. Abundances of cowries at six sites in northern Ningaloo Marine Park in July 2009. Areas sampled were inshore parts of the intertidal platforms, where cowries were most abundant. One transect was parallel to shore 60 m long and 3 m wide. Three transects perpendicular to shore were 20 m long and 3 m wide except for *, where there were only two transects, and for **, where the transects were 40 m long,

a. Numbers

Site	Number in sampled areas				Sum
	Parallel		Perpendicular		
	<i>caputserpensis</i>	<i>moneta</i>	<i>caputserpensis</i>	<i>moneta</i>	
Mildura Wreck	129	0	61	6	196
Surfers South	0	73	0	45	118
Jurabi Out 1	162	0	23*	0*	185
Jurabi In 1	4	2	16	15	37
Jurabi In 2	27	3	5**	70**	105
Yardie Creek	15	20	13	6	54
Sum	337	98	118	142	695

b. Densities

Site	Number m ⁻²					1-m ² quadrats Mean
	Parallel		Perpendicular		Means	
	<i>caputserpensis</i>	<i>moneta</i>	<i>caputserpensis</i>	<i>moneta</i>		
Mildura Wreck	0.72	0.00	0.34	0.03	0.27	0.00
Surfers South	0.00	0.41	0.00	0.25	0.16	0.13
Jurabi Out 1	0.90	0.00	0.19	0.00	0.27	0.42
Jurabi In 1	0.02	0.01	0.09	0.08	0.05	0.18
Jurabi In 2	0.15	0.02	0.01	0.19	0.09	0.38
Yardie Creek	0.08	0.11	0.07	0.03	0.08	0.15
Means	0.31	0.09	0.12	0.10	0.15	

Analysis of variance of $\log_{10}(\text{Number m}^2 + 0.01)$: Site is a random factor, Type and Species are fixed factors

Source	df	MS	F	p
Site	5	0.04761	0.0903	0.9926
Type	1	0.00001	0.0000	0.9967
Species	1	0.41399	0.7848	0.3896
Type*Species	1	0.32723	0.6203	0.4432
Residual	15	0.52749		

Table 7. Occurrence of *Cypraea caputserpentis* and *C. moneta* at different spatial scales.

a. By sites in Ningaloo Marine Park visited between one and four times between August 2007 and February 2010. Two-by-two permutational contingency test gave $p = 0.0606$, but regular chi-square test gave $p = 0.0303$, suggesting a positive association between the species.

<i>Cypraea cauputserpentis</i>		<i>Cypraea moneta</i>		Total
	Details of presence of both species	present	absent	
present	both always 5	18	5	23
	both sometimes 5			
	<i>C. moneta</i> always 7			
	<i>C. caputserpentis</i> always 1			
absent		5	7	12
Total		23	12	35

b. By quadrats:

i) northern Ningaloo Marine Park: four sites visited three times. Permutational 2 x 2 contingency test $p = 0.0203$. Pearson residuals indicate an excess of both present. All three tests done on data from individual sites showed that the two species occurred at random with respect to each other within sites.

<i>Cypraea cauputserpentis</i>	<i>Cypraea moneta</i>		Total
	present	absent	
present	4	4	8
absent	32	200	232
Total	36	204	240

Table 7-b concluded

ii) in southern Ningaloo Marine Park: 6 sites visited twice. Permutationa 2 x 2 contingency test $p = 0.4943$ All three tests done on data from individual sites showed that the two species occurred at random with respect to each other.

<i>Cypraea cauputserpentis</i>	<i>Cypraea moneta</i>		Total
	present	absent	
present	5	40	45
absent	36	186	222
Total	41	226	267

Table 8. Numbers of *C. caputserpentis* (c.), and *C. moneta* (m) found in different microhabitats at six sites. Superscripts indicate a deficit (d) or excess (e) judged by large Pearson residuals in a permutational 2 x k contingency test.

Microhabitat	Mildura Wreck 441 m ²		Surfers South 270 m ²		Jurabi Out 1 210 m ²		Jurabi In 1 270 m ²		Jurabi In 2 477 m ²		Yardie Creek 570m ²		Pooled 2238 m ²	
	c	m	c	m	c	m	c	m	c	m	c	m	c	m
>5 cm sand level	4	1		7			3			7			d ₇	e ₁₅
>5 cm sand in depression	6			12			2	1		4			d ₈	e ₁₇
<5 cm sand level	15	1		2	13		1	5	1	3	2	4	32	e ₃₃
<5 sand in depression				2			1	1		3		2	1	e ₈
Bare rock smooth	9			3	2				2	2			13	5
Bare rock rough	67			21	82		7	7	8	21	5	4	169	53
Bare rock in depression	64								1				e ₆₅	d ₀
Bare rock underside	1			7						2			1	e ₉
1-3 cm Algal bound sand smooth	3	e ₂		2						2			3	6
1-3 cm Algal bound sand rough	1				1			1		2			2	3
1-3 cm Algal bound sand in depression	1			1				1					1	2
Algae in depression	2	e ₃		2	1					12	1		d ₁₃	e ₃₅
Algae on surface				3										e ₃
Algae species	4				1						7	4	12	4
Underside of loose rock	58	2			61		4		e ₁₇	d ₈	4		e ₁₄₄	d ₁₀
Underside of loose rock in depression				1	1								1	1
Loose rock/rubble smooth									1		6	4	7	4
Loose rock/rubble rough	1			1			1	1	2	3	3	7	7	e ₁₂
Loose rock/rubble in depression			e ₁₇	d ₁					e ₄		1		22	1
Total	236	9	17	65	162	0	19	17	36	69	29	25	508	221
Permutation test, p	0.0014		<0.001		no test		0.1455		<0.001		0.274		<0.001	

a.

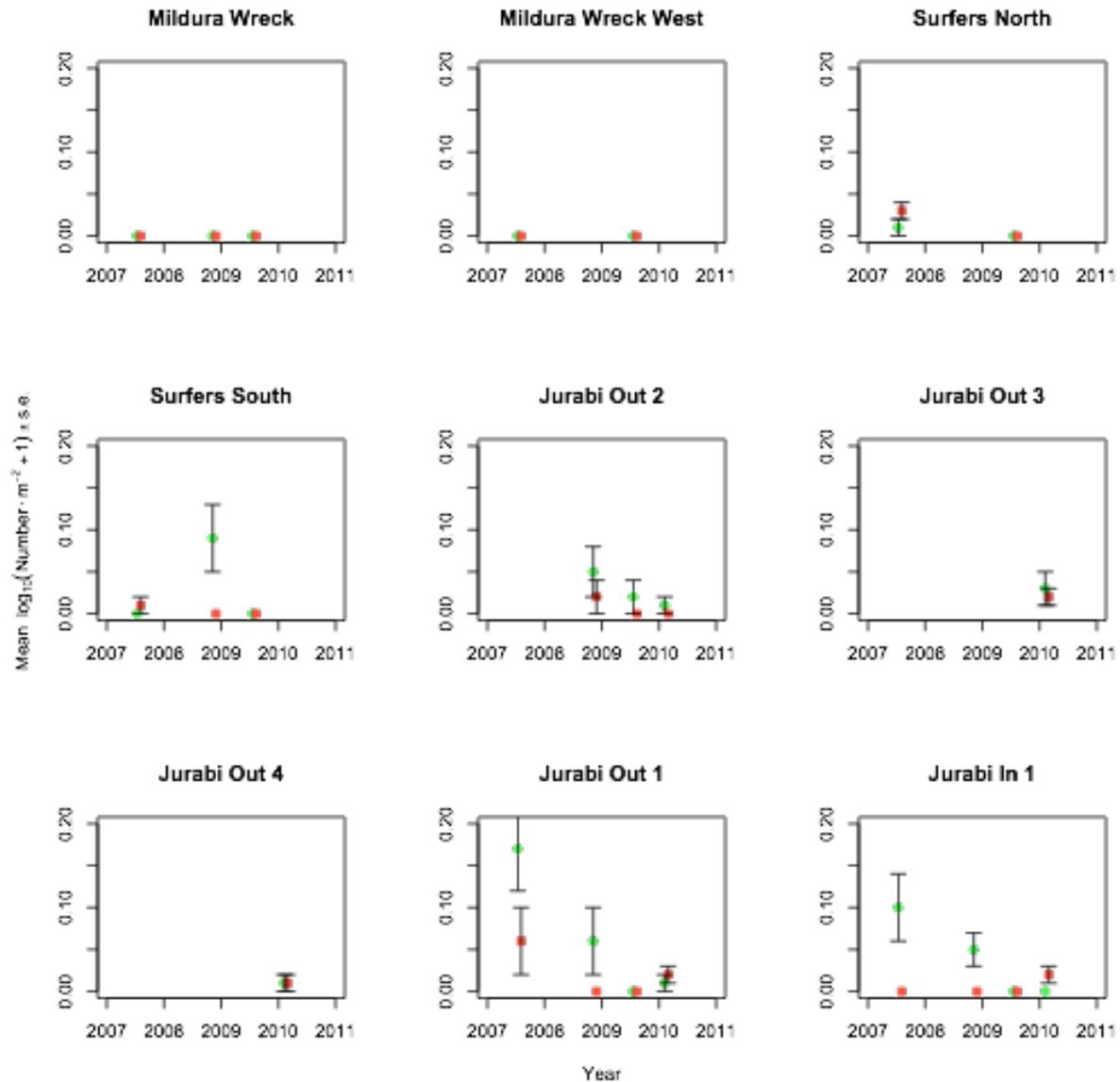


Figure 1. Abundances of *Cypraea moneta* (green circles), and *C. caputserpentis* (red squares) at sites sampled at least once between August 2007 and February 2010. The dates for the species are slightly offset so that the symbols do not overlap. Abundances are in logarithmically transformed units so that 0.0 and 0.2 represent 0 and 0.58 m^{-2} . The number of 1-m^2 quadrats used to calculate the means varied but was usually 20. Points without standard error bars indicate the absence of cowries. The 35 sites are shown in order from north to south in each panel. Panels b, c, and d are on the next pages.

b.

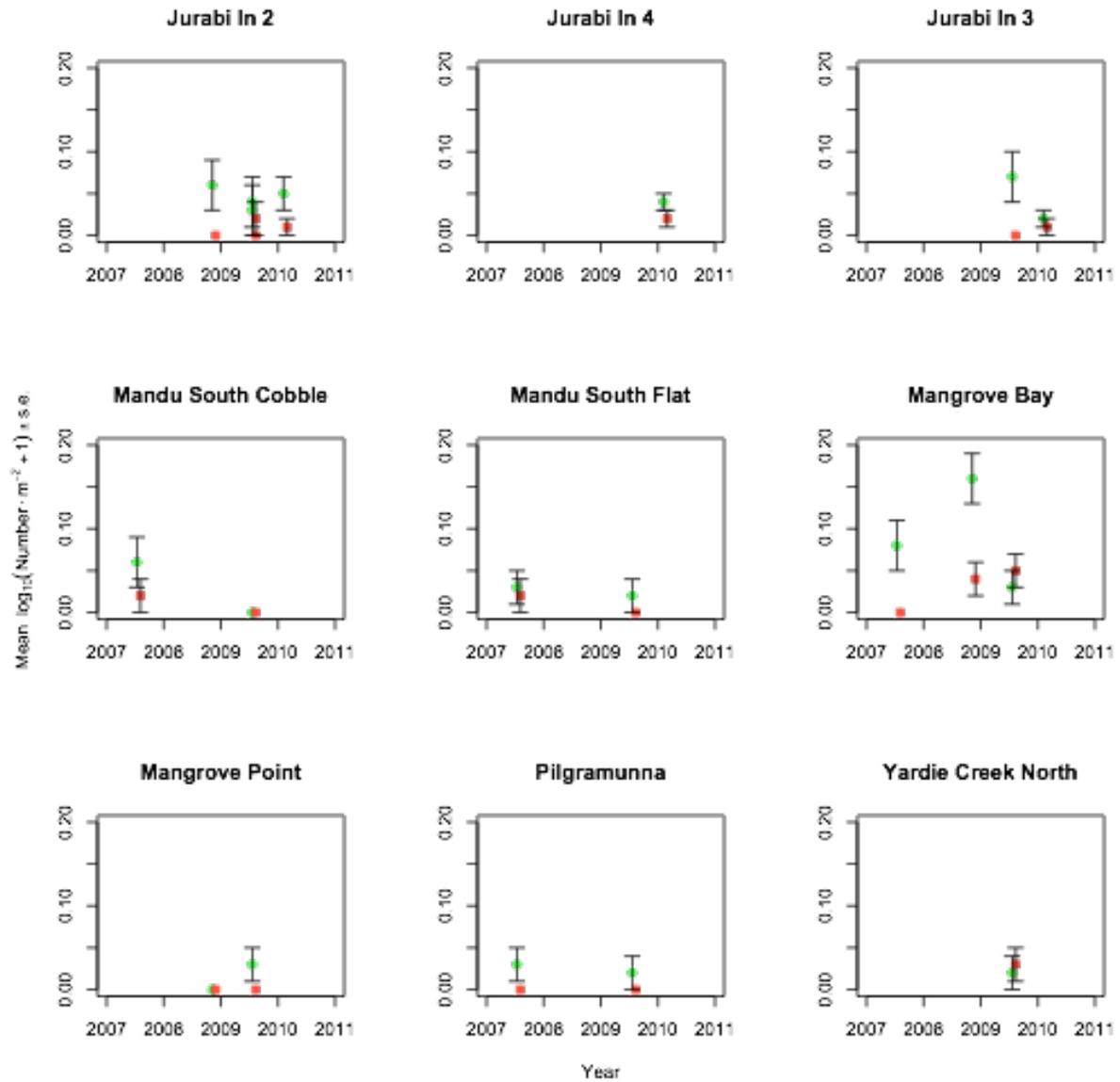
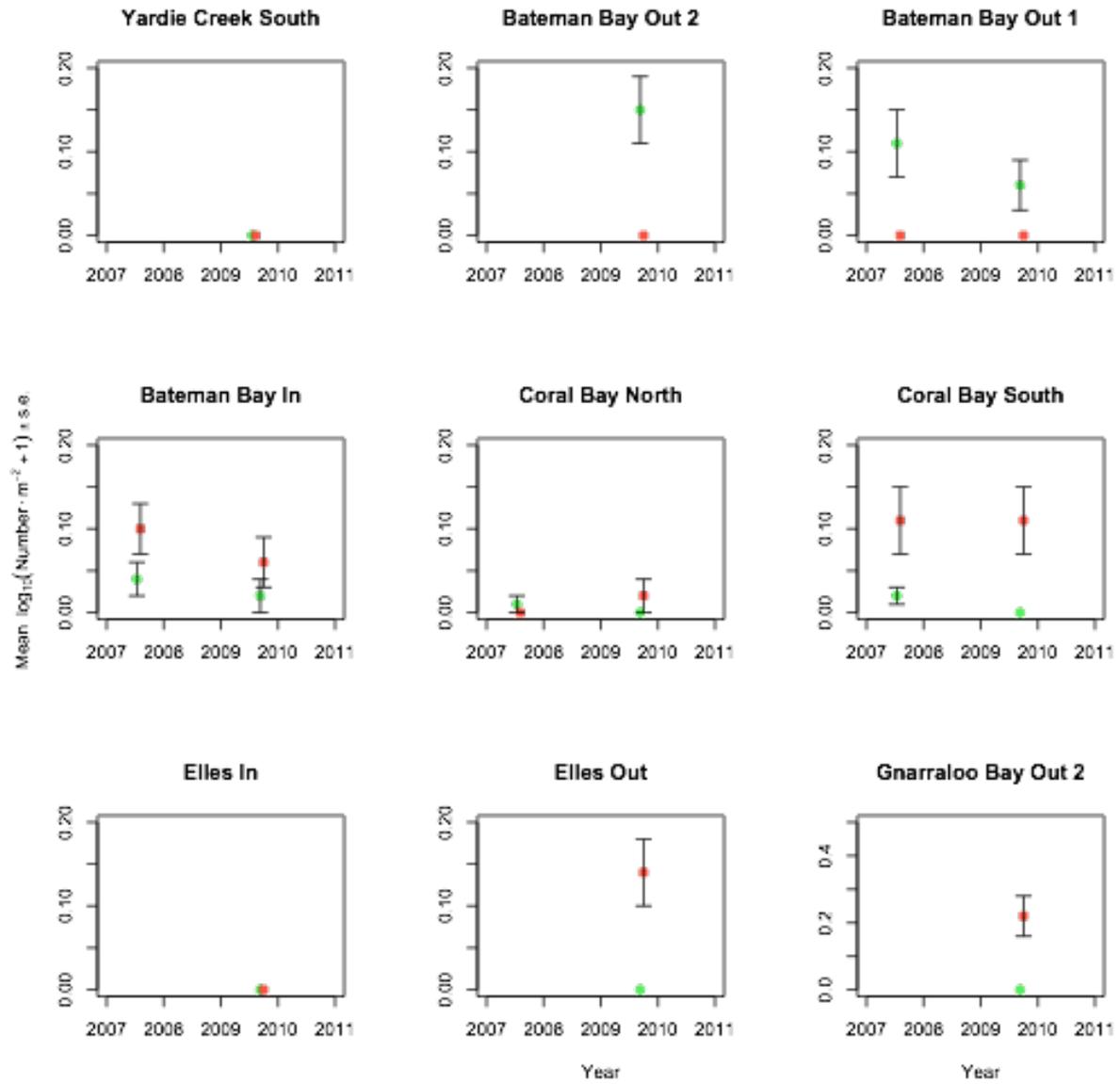


Figure 1. continued

c.



d.

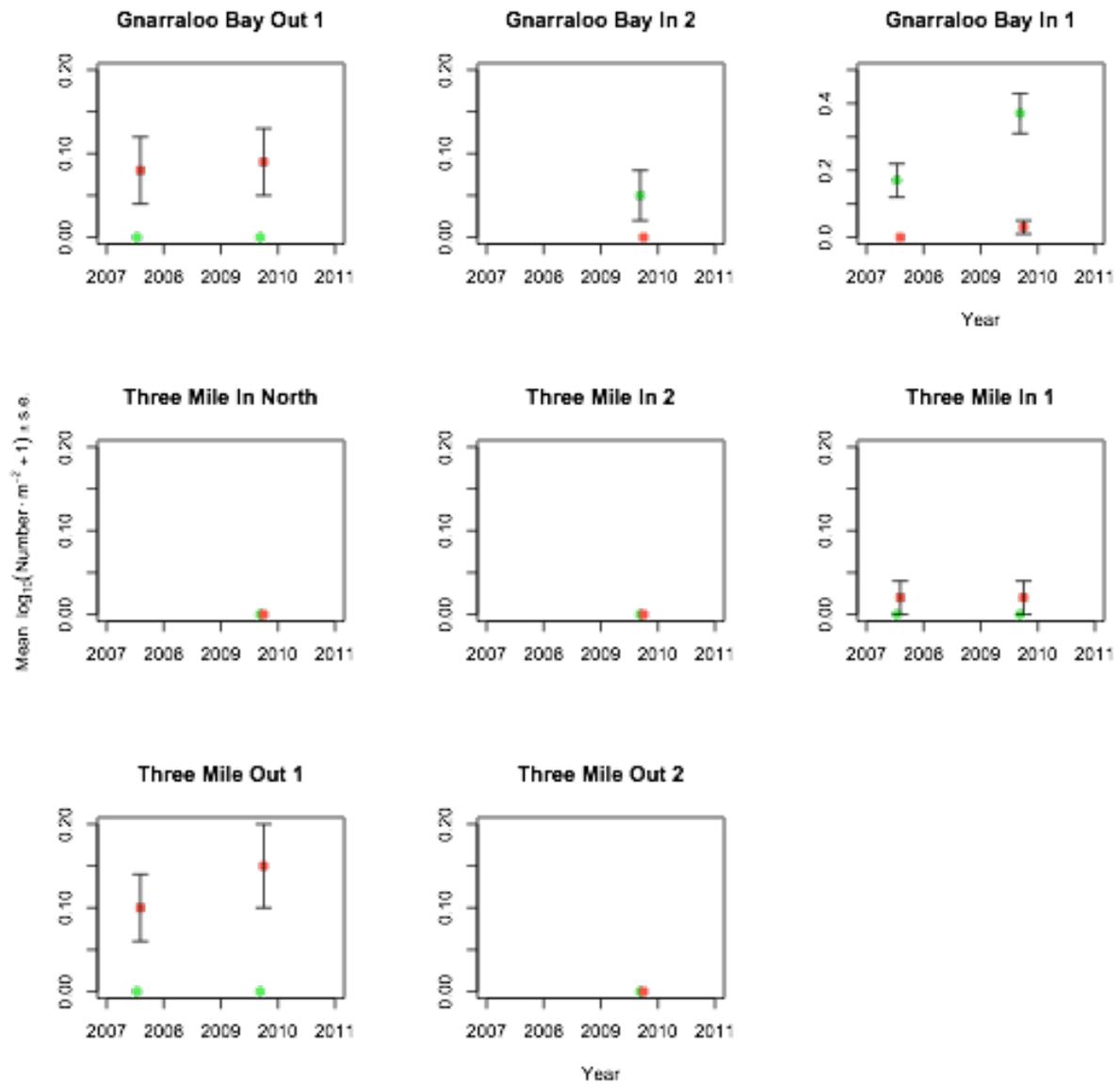


Figure 1. concluded. The scale of abundance for Gnarraloo Bay In 1 is larger than the others.

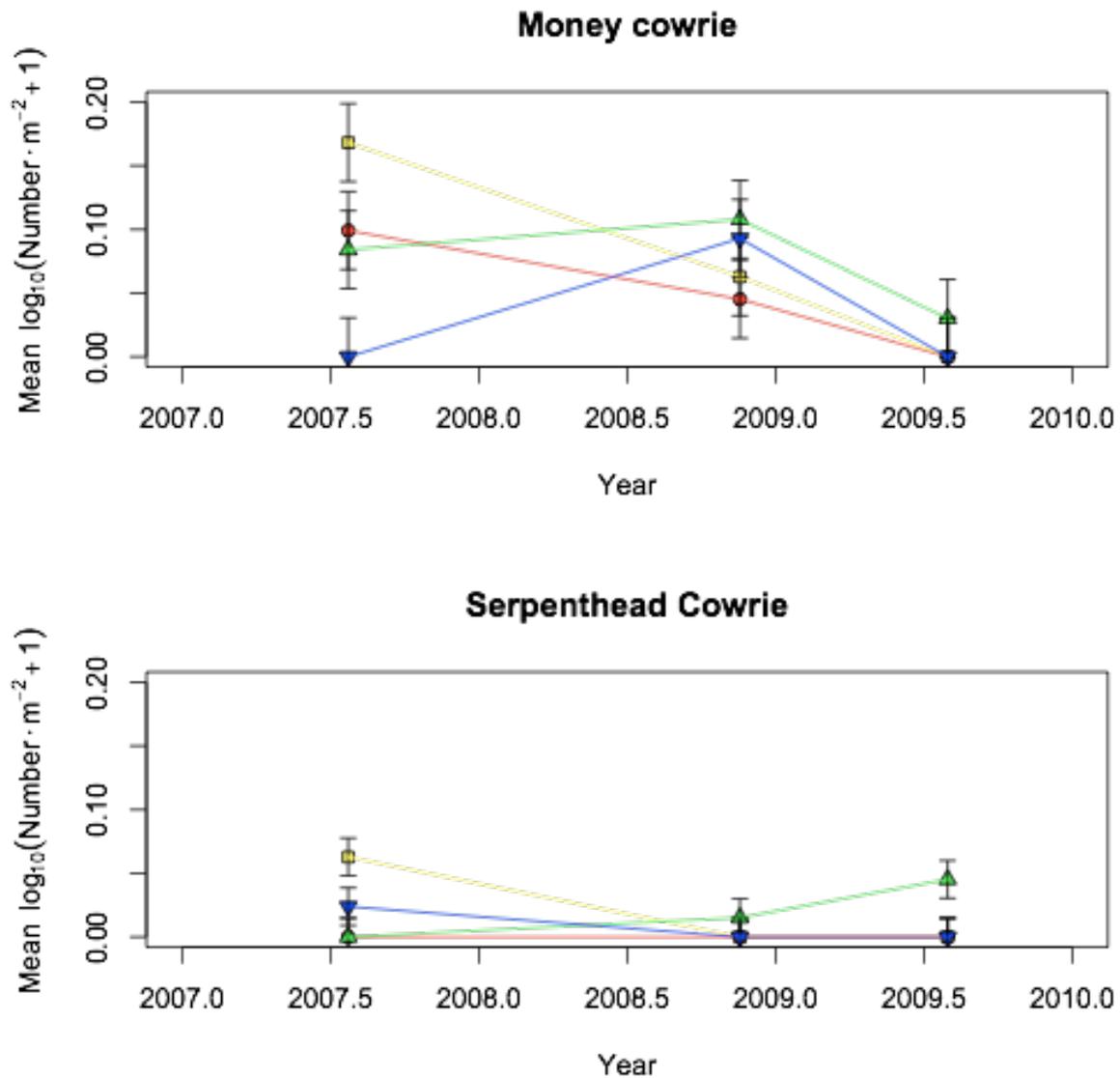


Figure 2-a. Interaction plots of abundances of cowries at sites -in northern Ningaloo Marine Park visited three times. The sites are from north to south: Surfere South (upward green triangles and lines); Jurabi Out 1 (yellow squares and lines); Jurabi In 1 (red circles and lines); Mangrove Bay (blue downward triangles and lines). The Y-axis is in logarithmic units with a transformation so that 0.0, 0.1, and 0.2 -are equivalent to 0, 0.25, and 0.58 individuals m^{-2} . The error bars are the common least squares standard errors from analyses of variances with site and date considered as random factors (see Table 4a).

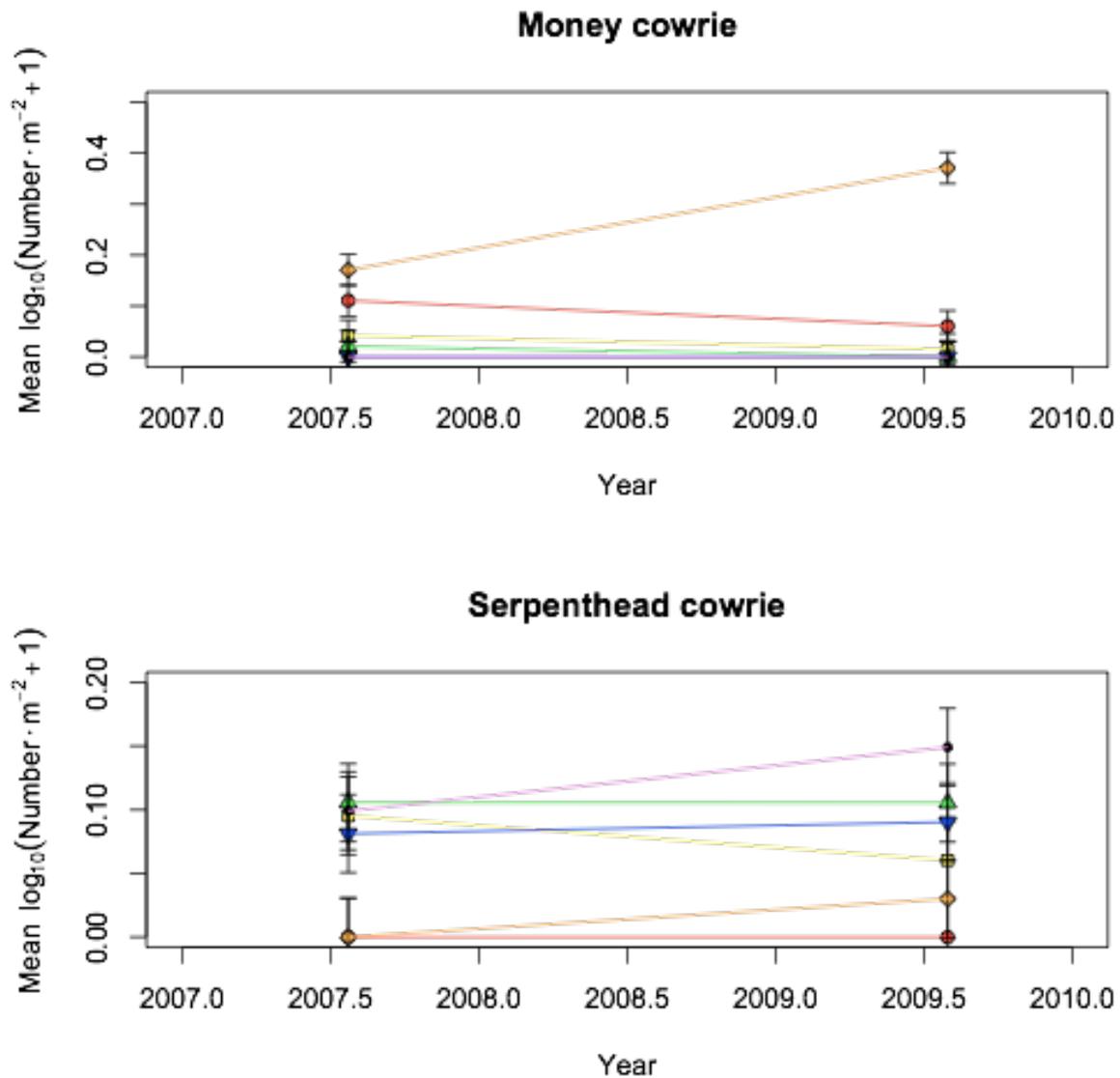


Figure 2-b. Interaction plots of abundances of cowries at several sites in the southern Ningaloo Marine Park visited twice. The sites are from north to south: Bateman Bay Out 1 (red circles and line); Bateman Bay In (yellow squares and line); Coral Bay South (green upward pointing triangles and line); Gnarraloo Bay Out 1 (blue downward pointing triangles and line); Gnarraloo Bay In 1 (orange diamond and line); Three Mile Out 1 (small circle and violet line). The Y-axis is in logarithmic units with a transformation so that 0.0, 0.1, and 0.2 are equivalent to 0, 0.25, and 0.58 individuals m^{-2} . The error bars are the common least squares standard errors from analyses of variances with site and date considered as random factors (see Table 4b).

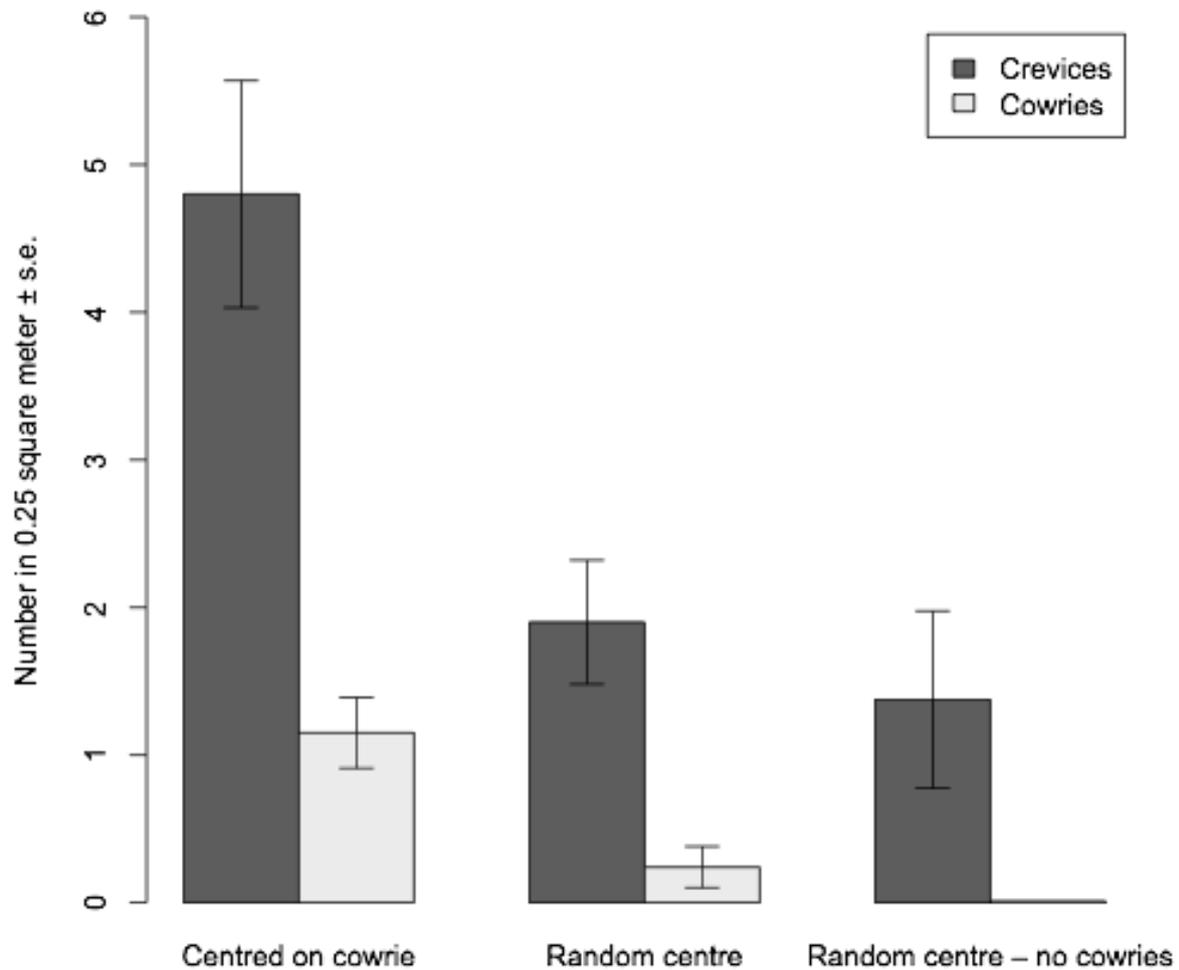


Figure 3. Number of crevices and cowries \pm s.e. in 0.25-m² quadrats in inshore parts of the intertidal platform at Mildura Wreck, February 2009, where *Cypraea caputserpentis* were abundant (left and middle pairs of bars based on 20 and 21 quadrats), or absent (right pair of bars, 16 quadrats). There were significantly more crevices and cowries in quadrats centered on cowries than the other two conditions, by Tukey's HSD post hoc tests.

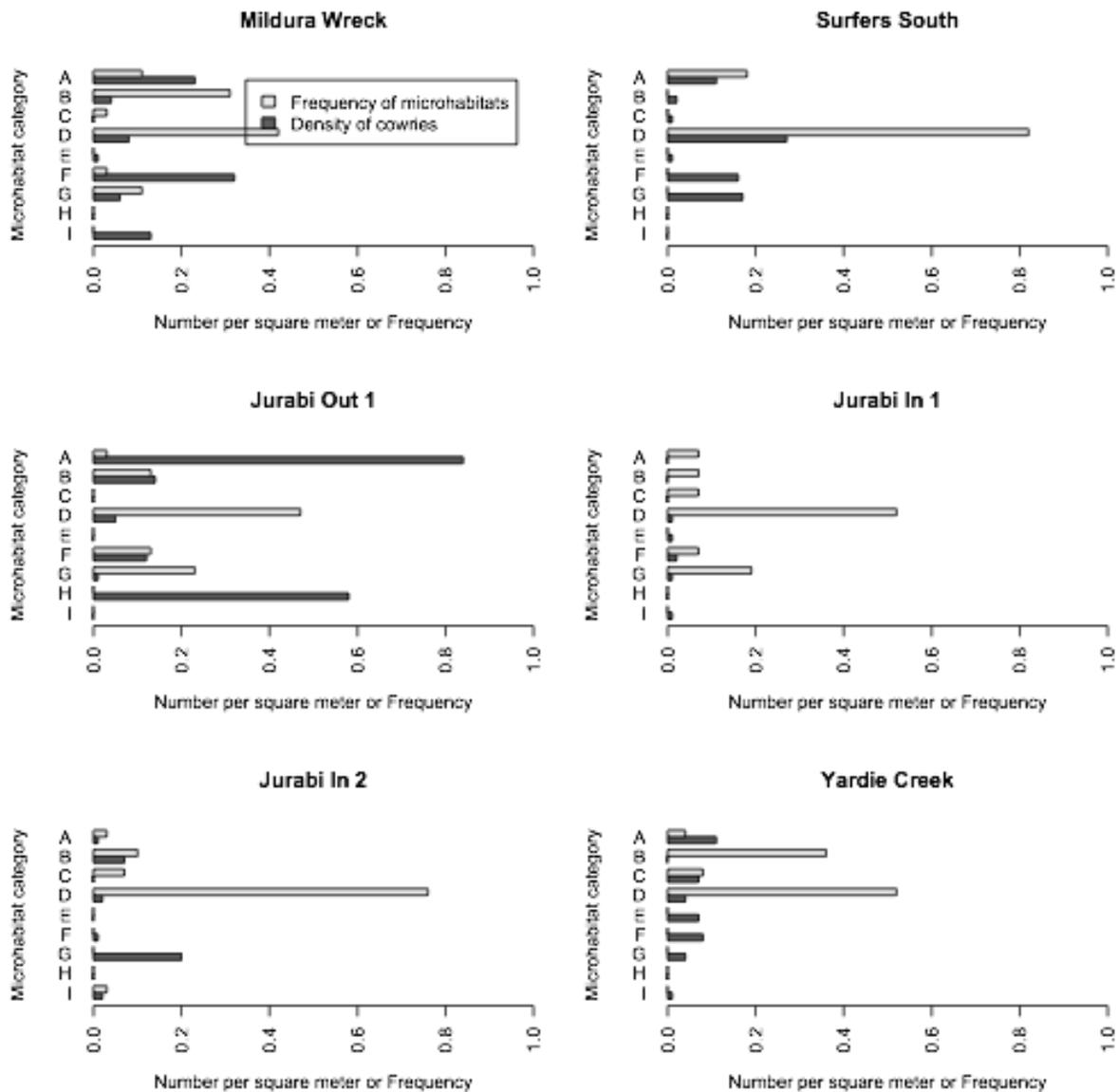


Figure 4 a. Frequency of occurrence of microhabitats and density (number•m²) of cowries in the belt transects parallel to shore at six sites in northern Ningaloo Marine Park. The microhabitat categories are:

Code	Description	Code	Description
A	Algae	F	Refuge in bare reef rock
B	Algal bound sand	G	Refuge in sand
C	Exposed on loose rock/rubble	H	Seagrass
D	Exposed on sand or bare rock	I	Under side rock
E	Protected loose rock/rubble		

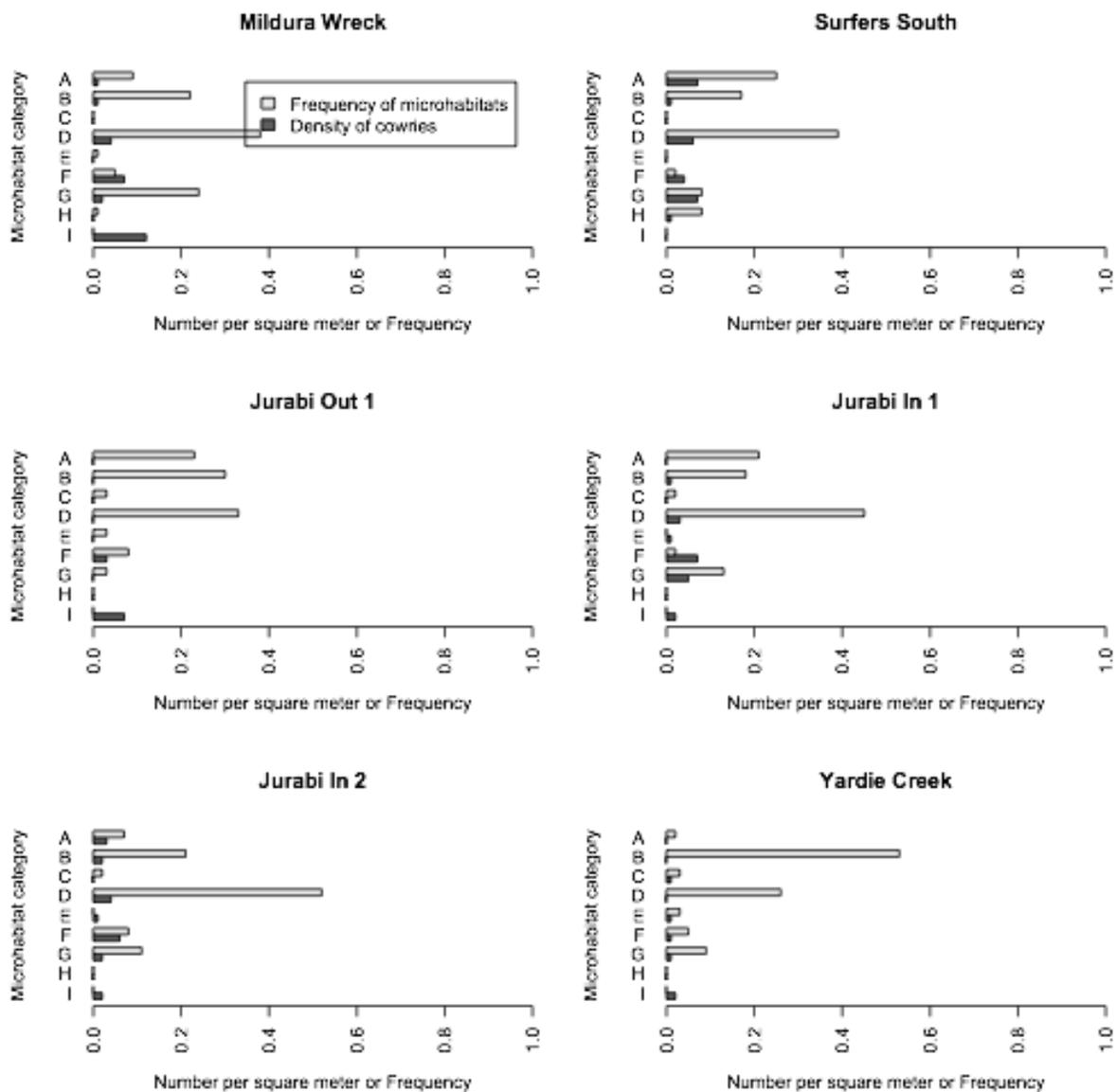


Figure 4 b. Frequency of occurrence of microhabitats and density (number•m²) of cowries in the belt transects perpendicular to shore at six sites in northern Ningaloo Marine Park. The microhabitat categories are:

Code	Description	Code	Description
A	Algae	F	Refuge in bare reef rock
B	Algal bound sand	G	Refuge in sand
C	Exposed on loose rock/rubble	H	Seagrass
D	Exposed on sand or bare rock	I	Under side rock
E	Protected loose rock/rubble		

**Chapter 4: Evidence of large, local variations in
recruitment and mortality in the small giant clam,
Tridacna maxima (Röding, 1798), at Ningaloo Marine
Park, Western Australia**

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Evidence of large, local variations in recruitment and mortality in the small giant clam, *Tridacna maxima* (Röding, 1798), at Ningaloo Marine Park, Western Australia

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Abstract

Understanding variability of recruitment and mortality is essential for assessing changes due to perceived disturbances or attempts to conserve populations. In the absence of long-term studies, we examined population density and size-frequency distributions of the small giant clam, *Tridacna maxima* (Röding, 1798), at 20 sites in Ningaloo Marine Park, Western Australia, where the clams are abundant on discontinuous, intertidal rocky platforms attached to the shoreline. Abundance ranged over two orders of magnitude ($0.05 - 8 \text{ m}^{-2}$), and size ranged from 1.5 to 31.0 cm. The shapes of the size-frequency distributions varied substantially, indicating variability in recruitment and mortality, including failures of cohorts to recruit and catastrophic events of mortality. Consistency of recruitment, as indexed by the coefficient of variation of the size-frequency distribution, was greater toward the north of the park, on intertidal platforms with greater complexity across their widths, and with smoother surfaces in the part of the platform occupied by the clams. The average turnover time was estimated at 5.5 years, giving a median age of 13 years. Variation among sites was large, however, highlighting the importance of variability of the dynamics of local populations, and the need for long-term studies to understand any particular population.

Additional keywords: intertidal platforms, size-frequency distributions, population density

Introduction

Understanding both the averages and the natural variability of recruitment and mortality is essential for assessing possible changes due to perceived disturbances or attempts to conserve populations. Long-term studies provide the only direct means of determining such variability (see Likens 1988; Kareiva *et al.* 1993), but these are especially difficult for relatively long-lived species. Instead, many ecological surveys involve single visits to sites, and so provide a snapshot view of populations of organisms without any direct information about temporal dynamics. Nevertheless, size-frequency distributions from such surveys provide hints about dynamics, because size is related to age or stage in the life history of the organism, and therefore provides clues about recruitment and mortality. Analytical techniques for extracting interpretations about dynamics from the patterns in the size distributions address the general problem of how ecologists can understand what happened in the past, and what might happen in the future, based on one sample from one or a series of populations (King 1995; Ebert 1999). To obtain insight into variability, size-frequency distributions from multiple populations may be a surrogate for long-term studies, revealing both spatial variation and evidence of temporal variation in recruitment and mortality. In this paper, we use this approach as a first step towards understanding variation of abundance, recruitment and mortality in the small giant clam, *Tridacna maxima* (Röding, 1798), in the Ningaloo Marine Park, Western Australia.

Large size, conspicuously-coloured mantles, and wavy margins of the shells make giant clams a symbol of shallow, tropical seas and lagoons of the Indo-Pacific. Giant clams in the family Tridacnidae occur from the Red Sea and east Africa, through the Indian Ocean, to southeast Asia, Australasia, Melanesia, Micronesia and Polynesia in the eastern Pacific (Copland and Lucas 1988; CITES 2006; Othman *et al.* 2010). The flamboyant, upwardly-directed mantle tissue is packed with photosynthetic zooxanthellae (Norton *et al.* 1992), and giant clams live in clear, relatively shallow water, making them easily visible and accessible. Consequently, they are harvested for meat and shell in many places, and even wild-caught or cultured for the aquarium trade, as well as being a sessile, conspicuous, attractive feature of natural, shallow

tropical waters.

The small giant clam, *Tridacna maxima*, one of the species with the widest distribution, has a global conservation status of “Lower Risk/Conservation Dependent”, and in Australia is considered “widespread and abundant” (CITES 2006). Populations of *T. maxima* in the Ningaloo Marine Park, Western Australia, are exceptional for their location on rocky, intertidal platforms attached to shore, which makes them both amenable to study and especially accessible to increasing numbers of tourists. As a first step towards understanding the dynamics of these populations, we have measured abundance and size-frequencies at 20 sites in the Ningaloo Marine Park, to provide indications of the spatial and temporal variability of recruitment and mortality. This paper adds to the understanding of the distribution and abundance of *T. maxima* in Australia by examining populations on rocky intertidal platforms.

Materials and methods

In August and September 2010, we mapped and measured *Tridacna maxima*, at 20 sites, spanning approximately 250 km, in Ningaloo Marine Park, where our previous sampling of the macroinvertebrates on rocky intertidal platforms in 2007, 2008, and 2009 indicated that the clams were reasonably abundant (Fig. 1). During low spring tides at each site, we established parallel belt transects perpendicular to the shoreline in the parts of the platform occupied by the clams. To map the location of each clam on each transect, we used a tape measure, weighted at each end and attached to a lead-cored rope to provide a coordinate along the transect (x). These transects varied from 10 to 38 m long, with the zero end most shoreward. Coordinates perpendicular to the tape measure (y) were determined using 150 cm dressmakers’ tapes at low-density sites, or 1 m² quadrats assembled from four 0.25 m² quadrats where clams were most abundant. The width of the transects varied from 2 to 5 m. We searched systematically along each transect, using glass-bottomed buckets to assist detection of the smallest clams when the platforms were covered with water. We used a team of at least three people, one recording the data and the others measuring the length of each

clam to the nearest tenth of a centimeter with vernier calipers, and determining its x-y coordinates. We took GPS readings, in UTM units, at each end of the transect and sometimes at intermediate positions, to facilitate relocation of the transects in the future. From the ends of each completed transect, we carefully measured the positions of the two ends of the next transect before repositioning the tape measure, parallel to the previous transect. The number of transects was determined by our aim to measure at least 100 clams at each site, and by the depth of the water as the tide rose. In order to augment the numbers of clams, we sometimes mapped and measured clams that were beyond the ends of the transects. Table 1 lists the sites in order from north (code A) to south (code T) with their names, the latitude and longitude of the shoreward, southern corner of the mapped areas, area sampled and the number of clams. One of the sites (L, Coral Bay North no map) was not mapped, but was searched systematically in the same manner as the other sites.

The clams attach to the substratum with their hinge against it and the ventral margins of the valves facing upwards. We measured the maximum length of the valves, and, like McMichael (1974), we discovered that there were several sources of potential error in our measurements. The left and right valves can be of unequal length. The edges of the valves can be encrusted with fouling organisms, buried in sediments, or under other organisms. The largest clams exceeded the size of our calipers (24 cm) or had shapes that required estimations of the lengths. We attempted to minimize these errors, but they nevertheless introduce some noise to the size-frequency distributions.

From the overall size-frequencies, we identified the group of small clams that represented the most recent detectable cohort of recruits. The relative abundance of this group provided the most direct measure of recruitment at each site, but this gives no indication of consistency of recruitment at the site. As an index of consistency of recruitment among years at each site, we used the coefficient of variation (CV) of the length of the valves (Ebert and Russell 1988). The rationale is that consistent recruitment will produce a more flattened distribution, and the utility of using the CV was shown by Ebert and Russell's (1988) seminal study of recruitment in urchins.

We used information about the physical characteristics of the 20 sites collected as part

an earlier survey of benthic invertebrates to test for associations with variation of abundance and size-frequencies. At 19 sites (excluding the unmapped site L), we used chains that conformed to the undulations in the surface of the platform, and measured the straight-line distances between their ends to quantify rugosity of the surface. We calculated the ratio of the straight-line distance to the length of the chain, transformed as the arcsin(square root of the proportion) in degrees, as an index of rugosity. A medium-weight 740 cm chain was used to measure general rugosity (due to pools and ridges, for example), and a lightweight 200 cm chain was used to measure fine-scale unevenness. Rugosity at both scales could be important in providing refuge from excessive exposure during low tide. With this same perspective, we also estimated the tidal elevation of the middle of the platform (height), its width perpendicular to the shoreline, and its complexity (an index calculated from a differential GPS survey of topography of the platform, from high tide level to the seaward limit of the platform, that was sensitive to changes in gradient and the presence of large pools). For broad-scale physical variables of each of all 20 sites, we used the latitude of the site, the extent of offshore reefs (in meters out of 10 km centered on each site) measured from nautical charts, and heterogeneity of the coast (the distance, in meters, of coastline along a straight line 2 km long centered on the site).

We used the statistical program R version 2.10.1 (R Development Core Team, 2009) with the package *vcd*, version 1.2-7, (Meyer *et al.* 2006, 2009; Zeileis *et al.* 2007) to perform contingency table tests by permutations. The package *lattice*, version 0.18-3 (Sarkar 2010), produced the composite size-frequency plots. Correlations and multiple regressions were conducted with JMP version 7.0.2.

Results

Size-frequency distributions

Overall, we measured 3119 clams at the twenty sites spread along 2.09 degrees of latitude in Ningaloo Marine Park, from Mildura Wreck in the north to Three Mile in the south (Table 1). In the pooled data, the smallest clam was 1.5 cm and the largest 31.0 cm, with a median of 12.0 cm. The shape of the distribution of lengths with 0.5 cm class intervals suggested that there might be modes of small and large clams on each side of a main broad peak. We therefore divided the size range of the clams into four categories, < 7.0 cm, 7.0-14.9 cm, 15.0-17.9 cm, and 18.0-31.0 cm. However, the pooled size frequency distribution hides the variability in the shapes of the distributions shown at individual sites, so we present the size-frequency distributions for each site separately (Fig. 2).

Three features of variation among the size-frequency distributions stand out (Fig. 2). First, there were distinct modes of small clams at nine sites: B, C, D, E, G, H, P, R, and T. Second, the right side of the size-frequency distribution was truncated at some of the sites, especially sites J, P and Q. Third, two or more clams larger than 21.0 cm occurred at sites A, F, G, H, L, M, N and O. The sizes of clams varied a lot, although some adjacent sites shared some features.

A second way of viewing the heterogeneity of the patterns in the size-frequency distributions was provided by the permutational contingency test on the four size categories at the 20 sites (Table 2). By this analysis, excesses of the smallest size class were found at sites B, D, H and I in the north and sites J, P and Q in the south, and deficits at site G in the north and sites L, M, N, O, R and S. Similarly, excesses of one or both of the two largest size classes were found at site G in the north and sites L, M, N, O, S and T in the south, with deficits at sites J, K, P and Q in the south. Therefore, of the nine northern sites, four had proportionally more of the smaller size classes and six had proportionally fewer of the largest size class. Although the trend at this large geographic scale was for northern sites to have relatively more small clams and fewer large ones, these geographic differences were not statistically

significant.

As can be calculated from Table 1, the overall densities of clams varied by about two orders of magnitude among sites, from more than 8 m^{-2} at site R to 0.05 m^{-2} at site B. Thus, a third perspective on the pattern of size-frequency distributions comes from the densities of the four size classes of clams. The mean densities of the four were variable, just as the overall densities were. As expected from the way the size classes were chosen, the mean densities of the smallest and largest size classes were least (0.09 m^{-2} and 0.07 m^{-2} respectively), and the smaller of the intermediate size classes greatest (0.56 m^{-2}). However, the relative variability among sites, as judged by the coefficient of variation of the densities, was much smaller for the smallest size class (140%) than for the others (235%, 210%, 222%) or the total density (213%), suggesting a consistency of density not shared by the other, larger sizes.

The proportion of the smallest size group, calculated from Table 2, gave an estimate of the size of the most recent cohort of recruits, which averaged 18.1% over the 20 sites, with a range of 1.0 to 51.9%. This translates to a mean turnover period of 5.5 recruitment intervals ($1 / 0.181$). The CV of length of shells at each site, our index of consistency of recruitment, was highly correlated with the proportion of recent recruits (arcsin $p^{0.5}$ transformed, $r = 0.742$, $df = 18$, $p = 0.0362$), but not with the proportions of the other size classes.

Tests of associations of abundance and recruitment with physical characteristics

Associations of the densities of clams, calculated from Tables 1 and 2, with CV and seven physical variables ($^{\circ}\text{S}$, Offshore reef, 2 km heterogeneity, Complexity index, width, 200 cm chain, and 740 cm chain) were assessed by multiple regressions. The densities of all the clams and the two smaller size categories increased with increasing rugosity measured by the 200 cm chain (large values are smooth), and decreased with increasing undulations of the coastline (2 km heterogeneity); as well, the smallest size class was more abundant on wider platforms (Table 4). As judged by the standardized

regression coefficients, the influences of these physical features on the abundance of the clams were similar, with the small-scale rugosity being slightly more influential for the smaller intermediate-sized clams, and all the clams. These associations explained more of the variations in density of the smallest clams than for the other two categories, according to the values for the adjusted r^2 . There were no associations with the physical characteristics for the 15 - 17.9 cm and the >18 cm clams.

The proportion of the smallest size group (arcsin $p^{0.5}$ transformed), our measure of most recent recruitment, was associated with only one physical variable, extent of offshore reefs (Table 4); sites with less offshore reef had more of the smallest size class, although this pattern was not tight, with an adjusted r^2 of 0.22. The CV of sizes of the clams at each site, our index of frequent recruitment, was influenced by latitude, complexity and rugosity index from the 740 cm chain, which entered the multiple regression in that order, increasing the adjusted r^2 from 0.42 to 0.53 to 0.68 (Table 4). CV increased towards the north, increased with complexity across the entire width of the platform, and increased with rugosity index (= increasing smoothness over 740 cm). The standardized partial regression coefficients were 0.58, 0.51, and 0.43 respectively, so the relative importance of the three physical variables was similar, relative to the variation within each.

Discussion

Densities of Tridacna maxima at Ningaloo Marine Park

According to the compilation by Othman *et al.* (2010), *Tridacna maxima* has the most extensive distribution of all the ten species of giant clams, from 30°E to 120°W and 36°N to 30°S. Their summary of densities of giant clams includes 49 estimates for *T. maxima*, including three from Australia at Mermaid, Cartier and Ashmore Reefs, which at 158, 21.8 and 38.3 m^{-2} are among the highest in their data, although nowhere close to the exceptional abundance of up to 500 m^{-2} at Fangatau Atoll (Andréfouët *et al.* 2005). Besides the quantitative estimates from Australia (3), others

are for islands and atolls in the Pacific Ocean (13), Papua New Guinea (1), the Phillipines (20), Singapore (1), Thailand (10), and Vanuatu (11). Therefore, along with the study by Apte *et al.* (2010) in the Lakshadweep Archipelago, our study extends quantitative estimates of density of *T. maxima* farther into the Indian Ocean.

Comparison of the distributions of population densities with those summarised by Othman *et al.* (2010) and estimates from four other intensive studies (Gilbert *et al.* 2006; Chambers 2007; Apte *et al.* 2010; this study) provides a perspective on the abundance of small giant clams at Ningaloo Marine Park (Fig. 3). Not surprisingly, because of the focus on this species of clam, the sites in the four intensive studies have higher densities of clams than most of the records in Othman *et al.*'s compilation, which includes many estimates from locations where the clams are heavily exploited, and where other species of giant clam occur too. Nevertheless, sites with more than 1 m⁻² are still uncommon, so the sites H, O, R and S in Ningaloo Marine Park are noteworthy, even though they do not cover large areas. Secondly, of the four intensive studies, our study at Ningaloo Marine Park is the only one where clams were studied in the intertidal zone; the others were conducted in lagoons, using snorkels or SCUBA, as were most of the studies reported in Othman *et al.* (2010). Thus, populations of *T. maxima* at Ningaloo Marine Park are exceptional for their location on rocky, intertidal platforms attached to shore, which makes them very accessible and easy to study. It also makes them much more accessible to tourists and fishers, but the relatively high densities suggest that this has not had a major impact in the Marine Park.

From size-frequency distributions to interpretations about dynamics

Snapshots of populations, such as size-frequency distributions, by themselves, offer little direct information about dynamics, and how to progress from pattern to interpretations about process is a major ecological issue. Fortunately, other studies of the *T. maxima* provide some estimates about dynamics that can be used to make some qualitative statements about aspects of dynamics of the populations at Ningaloo Marine Park. The replication provided by the 20 sites helps to give reasonable

estimates of averages, while also indicating great variability of population dynamics over both space and time.

Size-at-age information is crucial, and Table 5 and Fig. 4 summarize relevant information from the literature. Small giant clams grown in culture in the Solomon Islands take two years to reach 7 cm, the upper limit of our smallest size class (Table 2). The CITES (2006) claim of 4 cm at 2 years seems in error. Gilbert *et al.* (2006) and Chambers (2007) consider clams less than 6 cm to be immature. *Tridacna maxima* is a simultaneous hermaphrodite with synchronized spawning (Lucas 1988, Gilbert *et al.* 2006), with a 10-day larval phase under laboratory conditions (Yamaguchi 1977; Lucas 1988). In Guam, spawning was induced only in winter (Yamaguchi 1977, reporting work by others), but in Papua New Guinea Gwyther and Monroe (1981, Tables I and II) induced spawning in all months except March, July and August, and in north Queensland Braley (1988, Tables 1 and 2) induced spawning in December through March. Spawning could be more seasonal at the southern limits of the distribution, which would produce more discrete cohorts of recruits. Giant clams are claimed to have erratic recruitment (Gwyther and Monroe 1981; Gilbert *et al.* 2006), apparently based on interpretations of size-frequency distributions. Direct measurements in north Queensland of *T. gigas* and *T. derasa* showed spatial and temporal variation, with just two large recruitments out of 18 in the unbalanced combination of five sites, five times, and the two species (Braley 1988). Therefore, our size category of <7.0 cm probably represents immature clams accumulated over the past two years, in many cases largely as single cohorts.

The ages of larger clams are less clear. The growth trajectory of clams at One Tree Island (Fig. 4, von Bertalanffy function solid line, Richards function short dashes) seems to match the estimates of Chambers (Table 5d), while the estimates from Green and Craig's growth equation (Fig. 4, long dashes) suggest slower growth. Nevertheless, all three suggest that it takes about 20 years for clams to reach 20 cm. Although Apte *et al.* (Table 5d) claim it would take considerably longer, up to 60 years, we suggest that the data from One Tree Island probably best represent size-at-age for Ningaloo Marine Park clams, but because of the slow approach to asymptotic lengths, it is impossible to judge how old the largest clams could be, based on these

equations.

These perspectives from growth rates help with inferences about dynamics, based on the size-frequency distributions at Ningaloo Marine Park. As a first approximation the mean percentage of the size class < 7.0 cm, which was 0.181, can be taken as the most recent cohort of recruits. This percentage was uncorrelated with the density of this smallest size class or the density of the rest of the population, and, excluding the outlier site O, density of the smallest size class and density of the rest were not correlated, implying that recruitment varies with features extraneous to the local population. On average, it would take 5.5 times this mean percentage of the smallest size class to replace the others ($1 / 0.181 =$ turnover time), implying a median age of clams of 13 years ($2 + 5.5 \times 2$), not an unreasonable time, based on the rates of growth. When these turnover times were estimated separately for each site using the data in Table 2, they ranged from 104.3 at site O to 1.9 at site P, neither of which could possibly be correct. These extreme values highlight that these populations are not at equilibrium, and recruitment and mortality must vary substantially over time as well as space.

Two other features of the size-frequency distributions also indicate that variation in recruitment or mortality or both must vary among sites and over time. The first feature is the multi-modal distribution of the three larger size classes at some sites, e.g., sites G, L and T (Fig. 2). If recruitment were constant, variation in rate of growth would make cohorts less distinct beyond their first years, so the multi-modality indicates variation in the abundance of cohorts among years. The second feature is a truncation on the right of the size-frequency distribution at sites such as B, Q and S. The truncation implies catastrophic mortality followed by recruitment, such as the mortality event reported by Adler and Braley (1989) for *T. gigas* and *T. derasa* at Lizard Island, Queensland in July 1985 (25% in six weeks). In sum, our results indicate that there is considerable temporal and spatial variation in the gains and losses of individuals to the populations of clams at Ningaloo Marine Park.

To consider mortality further, we used Ebert (1999, pp. 252-253) as a guide to apply Van Sickle's (1977) method of extracting estimates of survival from size-frequency

distributions and a growth equation. Of course, we have no site-specific information about growth of the clams at Ningaloo Marine Park, but as a first approximation we used the Richards function growth equation from One Tree Island, which has a latitude and shallow water habitat similar to Ningaloo Marine Park (Table 5b). The method considers only the right-descending limb of the size-frequency distribution. The sizes are converted to relative ages in the light of the growth equation (sizes in excess of the L_{∞} cannot be used). The slope of the natural logarithm of the numbers in each size class plotted against the converted size is used to calculate Z , the instantaneous mortality coefficient in the simple model $N_t = N_0 e^{-Zt}$ (Table 6).

Constant and continuous recruitment is assumed in this method, which is not likely, as argued previously. However, in the absence of any direct information, these estimates help provide tentative spatial and temporal scales. The lowest values of p in Table 6 are for sites E, J, P and Q, the latter three of which have truncated right sides of the size-frequency distribution (Fig. 2). The mean probability of surviving per year, p in Table 6, of 0.805 is a rough guide to how well the adults survive, and how long they might live. A cohort of 1000 adults would be reduced to 10 individuals in 21 years, and to 1 individual in 31 years at this survival rate. Green and Craig (1999) used a similar method to estimate Z as 0.30 per year ($p = 0.74$) for a subtidal population, so our higher value does not alter the existing view that the clams survive well and are long-lived, even in these intertidal habitats.

Associations with physical features

The physical variables associated with density and recruitment included variables at the spatial scale of our sampling of *T. maxima* at 20 locations. Higher densities of clams were found at sites with rough texture within 2 m of surface of the platforms, and which were within straight sections of 2 km shorelines, suggesting that closer investigation of these within- and between-site features may be revealing, especially for the smallest size class, which showed the strongest associations. Frequent recruitment was associated with two within-site features, smoothness over 7.4 m and complexity of the whole platform, and one feature at the largest scale of our study,

latitude. Current recruitment differed most with regard to extent of offshore reef within 10 km of the sites, another large-scale, between-site feature. Latitude and offshore reefs were correlated (northern sites had more offshore reef: $r = -0.5191$, $df = 18$, $p = 0.0190$), unlike the other pairwise combinations of the physical variables. Thus, it is unclear what their separate, independent influences in our tests of association reflect. However, the fact that the proportion of the smallest size class and the CV each were associated with a different one suggests that different aspects of these physical features, varying over 250 km, may be important. The patterns revealed by these tests for association of features of the populations of clams with the selected aspects of the physical environment were detectable because we sampled so many sites. Also, the patterns were complex, usually involving two or more variables with different spatial scales and of almost equal importance, so that understanding separate mechanisms and their interactions that these associations suggest will be a challenge. Nevertheless, the strong patterns of association with physical variables shown for CV and densities of the two smaller size classes, combined with the lack of such patterns for the two larger size classes, suggests that the patterns established during recruitment are overridden as time passes by substantial, unpredictable mortality.

The combination of short larval life and isolation of Pacific island lagoons led Yamaguchi (1977) to suggest that populations were sustained through local recruitment, an idea consistent with Benzie and Williams' (1997) genetic analysis at the large geographic scale of Western Pacific populations. This is unlikely to apply at the spatial scale of our sites in Ningaloo Marine Park because offshore reefs are discontinuous and the unenclosed lagoons are flushed continuously. Consistent with this interpretation, genetic connectedness of *T. maxima* along the Great Barrier Reef is high (average $F_{ST} < 0.003$) (Benzie and Williams 1997). Population genetics analyses of other species with planktonic larvae in Ningaloo Marine Park did not reveal extensive genetic differentiation at this spatial scale (Johnson *et al.* (1993, Table 2) for a muricid gastropod *Drupella cornus* - adults in populations <180 km apart had $F_{ST} = 0.007$).

Of course, even low amounts of gene flow can homogenize the genetic structure of separated populations over the long run, while ecological differences in spatial and temporal patterning of recruitment, and size-specific rates of mortality can produce remarkable differences in age-structure and abundances in the same, linked populations (Johnson and Black 1984). Certainly, our description of the size-frequency distribution and abundance of *T. maxima* at 20 sites in Ningaloo Marine Park can only hint at which of the many processes might be involved. Our study highlights the importance of directly studying dynamics of the populations, and suggests where to start if we wish to learn more about this magnificent animal. It also shows, however, the value of having many spatial replicates as partial surrogates in the absence of long-term studies, to demonstrate the variability of population dynamics in both space and time

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Table 1. Details of twenty sites in Ningaloo Marine Park, at which *Tridacna maxima* was censused in August and September 2010.

Code	Name	°S	°E	Area (m ²)	Number of <i>Tridacna maxima</i>
A	Mildura Wreck	-21.7854	114.1638	2600	117
B	Surfers North	-21.7870	114.1595	1098	143
C	Surfers South	-21.7912	114.1545	1680	104
D	Jurabi Out 2	-21.8461	114.0359	560	221
E	Jurabi Out 1	-21.8479	114.0312	168	131
F	Jurabi In 1	-21.8494	114.0262	282	105
G	Jurabi In 2	-21.8506	114.0250	480	157
H	Jurabi In 3	-21.8517	114.0233	180	195
I	Mandu Mandu South Flat	-22.1465	113.8696	304	166
J	Bateman Bay In	-23.0499	113.8234	720	164
K	Coral Bay North	-23.1532	113.7683	620	58
L	Coral Bay North no map	-23.1543	113.7680	2075	166
M	Coral Bay South	-23.1572	113.7664	1080	146
N	Elle's In	-23.4336	113.7815	1496	138
O	Elle's Out	-23.4383	113.7787	120	313
P	Gnarraloo Bay Out 2	-23.7607	113.5617	600	158
Q	Gnarraloo Bay Out 1	-23.7636	113.5580	480	82
R	3 Mile North	-23.8704	113.4970	30	248
S	3 Mile In 2	-23.8754	113.4942	120	198
T	3 Mile Out 2	-23.8794	113.4902	480	109

Table 2. Numbers of small giant clams in four size categories at each of the twenty sites in Ningaloo Marine Park, listed in order from north to south.

Superscripts indicate large Pearson residuals indicating excesses (2 to 4 = +, 4 to 11.1 = ++), and deficits (-2 to -4 = -, -4 to -6.86 = --) from random expectations in the contingency table. Permutational contingency test, $p < 0.001$.

Code	Name	Size class in cm			
		≤6.9	07.0-14.9	15.0-17.9	18.0-33.0
A	Mildura Wreck	23	58	25	11
B	Surfers North	44 ⁺⁺	72	24	3 ⁻
C	Surfers South	22	68	11	3 ⁻
D	Jurabi Out 2	59 ⁺	152 ⁺	6 ⁻⁻	4 ⁻
E	Jurabi Out 1	26	96 ⁺	6 ⁻	3 ⁻
F	Jurabi In 1	11	71	16	7
G	Jurabi In 2	16 ⁻	73	41 ⁺	27 ⁺
H	Jurabi In 3	52 ⁺	117	20 ⁻	6 ⁻
I	Mandu Mandu South Flat	44 ⁺	112	3 ⁻⁻	7 ⁻
J	Bateman Bay In	39 ⁺	123	1 ⁻⁻	1 ⁻
K	Coral Bay North	5	48 ⁺	5	0 ⁻
L	Coral Bay North no map	9 ⁻	79	40 ⁺	38 ⁺⁺
M	Coral Bay South	5 ⁻	67	35 ⁺	39 ⁺⁺
N	Elle's In	6 ⁻	25	54 ⁺⁺	53 ⁺⁺
O	Elle's Out	3 ⁻⁻	166	95 ⁺⁺	49 ⁺
P	Gnarraloo Bay Out 2	82 ⁺⁺	73	3 ⁻⁻	0 ⁻
Q	Gnarraloo Bay Out 1	36 ⁺⁺	46	0 ⁻	0 ⁻
R	3 Mile North	16 ⁻⁻	178 ⁺	36	18
S	3 Mile In 2	14 ⁻	101	69 ⁺⁺	14
T	3 Mile Out 2	15	49	33 ⁺	12

Table 3. The coefficient of variation (CV) of the lengths of shell of *T. maxima*, along with six of the physical variables measured at the twenty sites. Latitude is in Table 1.

NA = not measured.

Code	CV	Offshore reef, m	2 km heterogeneity	Complexity index	width	200 cm chain	740 cm chain
A	40.29	6355	2818	1.00098	185	77.48	79.20
B	44.14	2790	2507	1.00277	140	72.29	79.84
C	38.75	2868	2050	1.00113	143	77.41	80.54
D	38.73	7905	2143	1.00234	91	75.88	78.19
E	37.68	7905	2139	1.00038	88	73.94	79.19
F	35.43	3720	2133	1.00829	82	74.05	79.41
G	32.74	9688	2149	1.00322	139	77.61	79.41
H	44.08	5580	2139	1.00577	160	75.29	76.55
I	36.75	6510	2105	1.00369	100	71.23	78.78
J	29.32	232	2425	1.00011	104	66.74	81.03
K	27.57	232	2236	1.00003	29	70.18	78.99
L	30.99	232	NA	NA	NA	NA	NA
M	31.03	232	2218	1.00053	25	71	78.78
N	26.20	930	2248	1.00030	143	79.45	80.07
O	23.54	2170	2272	1.00030	80	69.38	81.28
P	44.45	3255	2072	1.01286	42	76.95	78.78
Q	31.70	2790	2112	1.00460	45	70.22	79.41
R	25.58	5192	2125	1.00380	201	63.26	73.17
S	25.75	6278	2162	1.01014	37	75.29	75.72
T	30.92	4882	2129	1.00062	36	79.69	81.28

Table 4. Relationship of densities of categories of *T. maxima*, proportion of the smallest size class, and CV of lengths of clams at each site with physical variables.

The independent variables were elected by forward, stepwise regression, which stopped when added independent variables had non-significant regression coefficients.

Transformations were used to make the residuals more evenly distributed.

Regressions for the two larger size categories of clams were non-significant. The number of sites is 19 because site L lacked most of the physical measurements.

Dependent variable, with adjusted r², p of overall model	Independent variables	Intercept and Regression coefficients ± s.e.	Standardized partial regression coefficient
Density of ≤6.9 cm clams		1.765 ± 0.43910	
	200 cm chain	-0.01361 ± 0.00475	-0.47
0.60, 0.0025	width (m)	0.00135 ± 0.00041	0.58
	2 km Heterogeneity	-0.00036 ± 0.00012	-0.52
log(density of 7.0 - 14.9 cm clams)		8.41515 ± 2.4079	
	200 cm chain	-0.08411 ± 0.02621	-0.58
0.41, 0.0057	2 km Heterogeneity	-0.00134 ± 0.00062	-0.39
log(density of all clams)		7.13956 ± 2.35400	
	200 cm chain	-0.06647 ± 0.02562	-0.50
0.32, 0.0175	2 km Heterogeneity	-0.00123 ± 0.00061	-0.39
arcsin(p ^{0.5} of ≤ 6.9 cm clams) in °		31.9084 ± 3.84884	
	Offshore reefs	-0.00190 ± 0.00074	-0.52
0.22, 0.0196			
CV		-893.122 ± 265.052	
	- °S	4.332 ± 1.090	0.57
0.68, 0.0001	740 cm chain	1.423 ± 0.4995	0.43
	Complexity index	910.372 ± 252.70	0.51

Table 5. Information from the literature on growth rate of *Tridacna maxima*.

a. Data transcribed from Figure 2 of Hart *et al.* (1998), Solomon Islands (11° 14' 40.83" S).

Age in years from spawning	Length in mm
0.00	0.50
0.76	23.73
1.15	38.43
1.46	49.24
1.69	57.67
2.00	68.41
2.24	77.89

b. Data of McMichael (1974), One Tree Island, Queensland, Australia (23° 30' 22.91" S). Table II shows sizes of individual clams mapped and measured on November 1966, September 1968, and November 1969 from which 43 records from first interval (1.81 years) and 267 records from the second interval (1.17 years) were used to fit a von Bertalanffy growth equation using the programs FABENS.BAS (Ebert 1999) which incorporated the size-at-age information from part a, above, and a Richards function using Ebert's RICHARDS.BAS. See Fig. 5 for plots of the curves.

von Bertalanffy Growth equation	
L_{∞}	209.97 ± 3.55 s.e. mm
K	0.1438 ± 0.00701 year ⁻¹
r ²	0.976358
residual SS	11390.546042
Richards function	
L_{∞}	233.86
K	0.06543
n (shape parameter)	-0.49498
b	1.03772

c. Analysis of Green and Craig (1999, Figure 4), Rose Atoll, Samoan Archipelago (14° 15' 24.33" S) of size frequency distributions of largest clams. See Fig. 5 for a plot of the curve.

von Bertalanffy Growth equation	
L_{∞}	27.8 cm

K	0.068 year ⁻¹
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d. Reports of Chambers (2007) citing Heslinga *et al.* (1990) and Lewis (1987), and Apte *et al.* (2010) citing another study of size-at-age information.

Size, cm	Chambers: Time to reach size, years	Apte <i>et al.</i> : Time to reach size, years	Chambers: Protandrous hermatphrdites - Sexual maturity	Apte <i>et al.</i> : size at transitions between stages
6			some as males	
10	5	10	50% of males, 50% of females	juvenile- subadult
14			100%	
15	10			
20	15-20	50-60		subadult-adult

Table 6. Estimates of Z , instantaneous mortality rate per year, of small giant clams at the twenty sites. p is the finite rate of survival, e^{-Z} , per year.

Code of site	Site	Z	p
A	Mildura Wreck	0.148	0.863
B	Surfers North	0.198	0.820
C	Surfers South	0.196	0.822
D	Jurabi Out 2	0.207	0.813
E	Jurabi Out 1	0.258	0.773
F	Jurabi In 1	0.202	0.817
G	Jurabi In 2	0.142	0.868
H	Jurabi In 3	0.151	0.860
I	Mandu South Flat	0.173	0.841
J	Bateman Bay In	0.274	0.761
K	Coral Bay North	0.184	0.832
L	Coral Bay North no map	0.145	0.865
M	Coral Bay South	0.168	0.846
N	Elles Out	0.170	0.844
O	Elle's In	0.119	0.888
P	Gnarraloo Bay Out 2	0.532	0.588
Q	Gnarraloo Bay Out 1	0.724	0.485
R	Three Mile North	0.185	0.831
S	Three Mile In 2	0.185	0.831
T	Three Mile Out 2	0.157	0.855

Figure captions

Fig. 1. Ningaloo Marine Park with the locations of the 20 sites at which *Tridacna maxima* was censused. Table 1 gives the precise location of each site.

Fig. 2. Size frequency distributions with intervals of 0.5 cm for the lengths of *Tridacna maxima* at twenty sites in Ningaloo Marine Park. The labels above the distribution for each panel are the codes listed in Table 1 which also gives the full names of the sites. The sites are in order from north to south from upper left to lower right.

Fig. 3. Frequency distributions of the logarithm of the mean number of *Tridacna maxima* reported in Othman *et al.* (2010, Table 1; 49 estimates) (second panel from bottom), and for other studies of multiple sites by Apte *et al.* (2010, Appendix: Juveniles, Sub-adults, and Adults pooled for each year, and averaged across years; 12 sites in the Lakshadweep Archipelago, 10°N, 72° 38'E) (top panel), Chambers (2007, Appendix 1; 27 sites, Tongareva Lagoon, Cook Islands, 9°S, 158°W) (second panel), Gilbert *et al.* (2006, Table 1; 9 locations in Society, Austral and Tuamotu Islands, ~19-23°S, 135-150°W) (third panel), and this study (Table 1; 20 sites, 21.7-23.9°S, 113.5-114.2°E in Table 1) (bottom panel).

Fig. 4. von Bertalanffy growth curves for *Tridacna maxima* at One Tree Island using data from McMichael (1974, Table 2), and information from Hart *et al.* (1998, Figure 2) about size-at-age from spawning to 2.24 years (solid line), and using equation quoted in Green and Craig (1999) (long dashes). The curve of short dashes is a fit to a Richards growth function to the 264 data points for growth between 1968 and 1969 from the One Tree Island data set. See Table 5b and c for the estimates of the parameters of the growth equations and the standard errors for the One Tree Island curves.

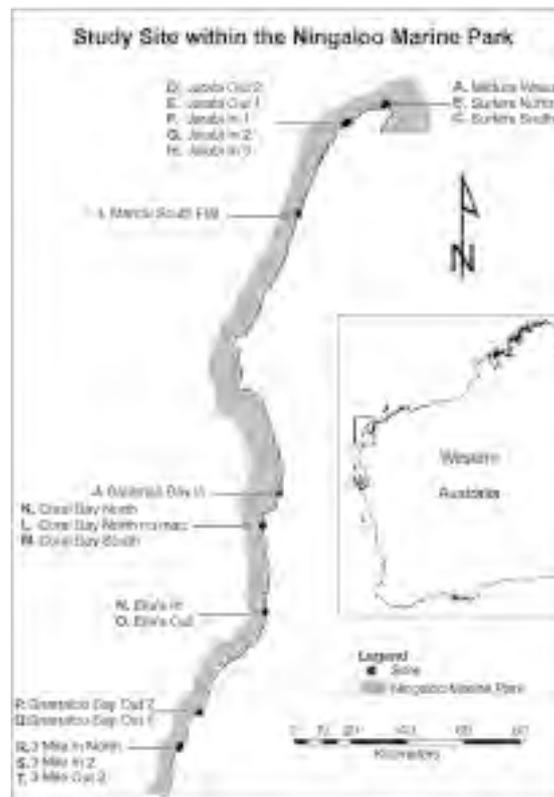


Figure 1

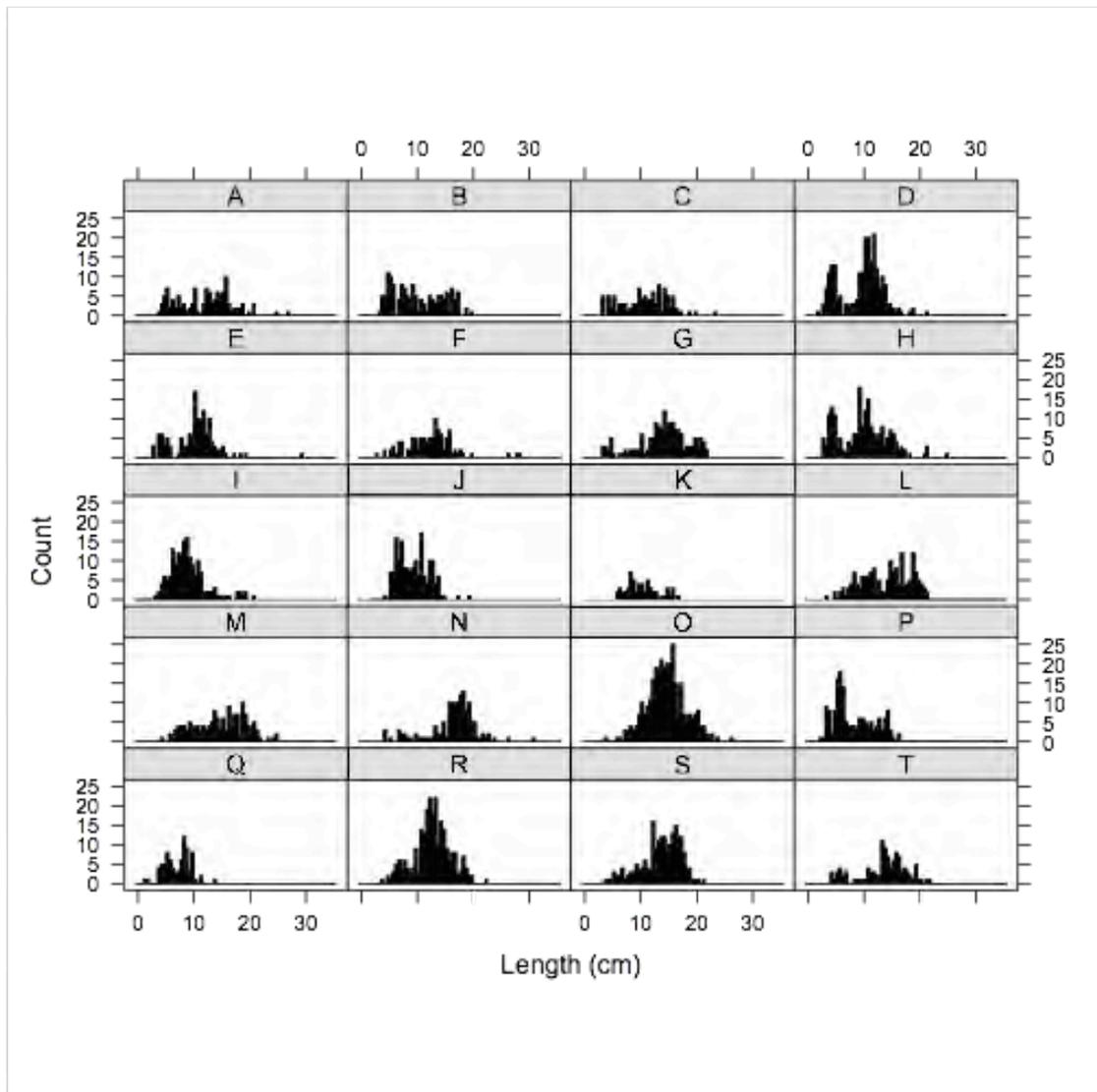


Figure 2

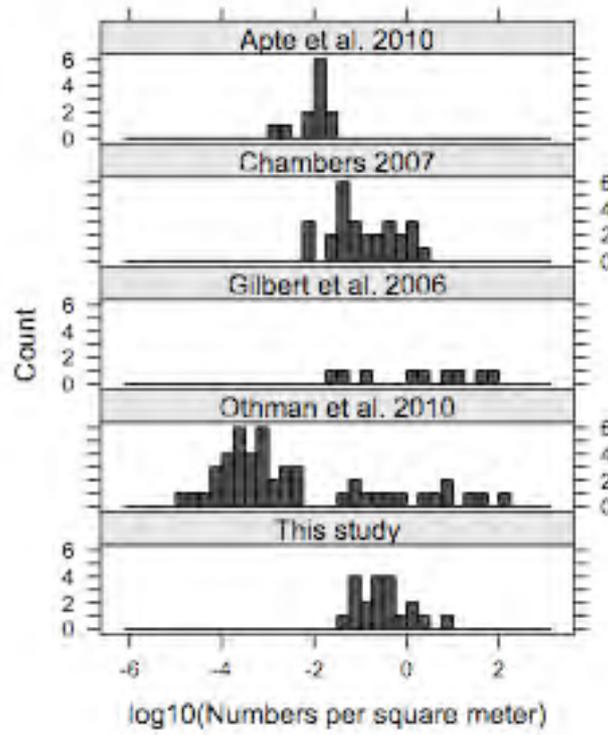


Figure 3

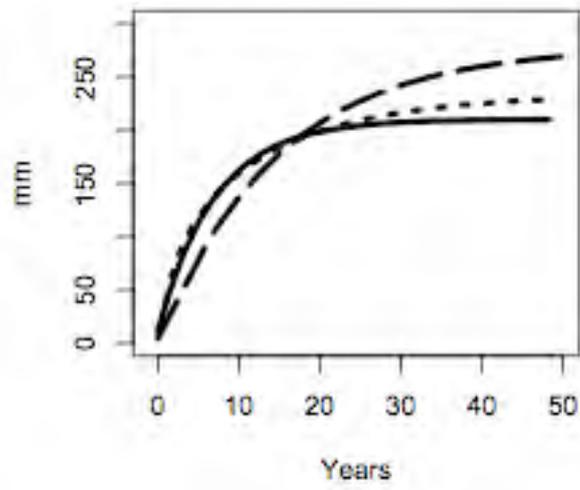


Figure 4

**Chapter 5: Spatial and temporal
variability in abundance of 15 selected
species of invertebrates at 18 sites in
Ningaloo Marine Park, 2007 and 2009.**



Introduction

The ability to detect differences between sites or sites of particular categories and changes over time depends on how much variation there is from place to place and from one time to another. As outlined in Chapter 1, we sampled the assemblages of animals on rocky intertidal platforms in Ningaloo Marine Park in order to determine the distribution and abundance of each of the species in the assemblages. This chapter estimates spatial and temporal variability of 15 selected species of invertebrates at 18 sites in the Park, from Mildura Wreck in the north to Three Mile in the south, each sampled in 2007 and 2009.

Methods

The 15 species of invertebrates were selected because they were among the most abundant species. Ten were gastropods, three were bivalves, one a coral and one a sea urchin (Table 1). The coral and small giant clam (*T. maxima*), get some of their energy from endosymbiotic zooxanthellae, as well as from small particles in the water. The bivalves are suspension feeders, depending on particles in the water. The vermitid uses mucus threads to capture particles from the water. The ceriths and the stromb probably feed on small organic particles in sediments. The turban shell, trochid and sea urchin are herbivores. The thaidis and cone are predators. Thus, this selection of species includes examples of most kinds of feeding by marine organisms. The coral, the bivalves, and the vermetid are permanently attached to the surface of the platform, and the urchin is usually associated with a depression in the surface, while the remaining species can move.

Table 2 shows how the 15 selected species were distributed among the 18 sites that were sampled with about 20 replicate 1-m² quadrats in August 2007 and exactly 20 replicate quadrats July and September 2009. The column labeled N in the table is the sum of the quadrats in the two years.

The 18 sites include four pairs of sites that are nearby each other but on opposite sides of the

northern boundaries of the sanctuary zones at Jurabi, Bateman Bay, Gnarraloo Bay, and the southern boundary at Three Mile. The names of these sites include “In” or “Out” to indicate their relationship to the sanctuary. Of the remaining 10 sites only Pilgramunna is outside a sanctuary zone, and the others are in Lighthouse Bay, Mangrove Bay, Mandu, and Maud Sanctuary Zones. Thus, sanctuary zones in all five regions in the Park accessible from land are represented in the 18 sites.

The design of the data on abundance of each species was a factorial one in which each level of site was crossed with each level of year of sampling, with the replicate 1-m² quadrats nested within the combinations of site and year. Because the selection of species determined what sites were involved for that species, and because we were concerned about the sampling in 2007 and 2009, we have considered both Site and Year as fixed factors in the analyses of variance, which were conducted with the software JMP Version 7.0.2. In order to provide a quantitative estimate of the magnitude of spatial and temporal variability, we calculated the % magnitude of experimental effects for each term in the model according to formulae in Winer (1971, pp. 428-430), implemented in a spreadsheet. Magnitude of experimental effects is also known as omega squared (ω^2). In the analyses of the abundances of these species, the numbers in each 1-m² quadrat were transformed by taking the logarithm to the base 10 of the number + 1 ($\log_{10}(x + 1)$), which helps make variances homogeneous and makes relative changes obvious in plots of abundance.

For the four pairs of sites that were on opposite sides of a boundary of a sanctuary zone, we used the four levels of Zone as a random blocking factor for the two levels of Status (In or Out) crossed with the two levels of Year (2007 and 2009). The latter two factors are fixed. Using Zone as a blocking factor accounts for the variability among zones that might arise because they are in different parts of the Park, for example, thus allowing a more precise comparison of the fixed factors. Because the replicate quadrats are nested within the 16 combinations of the levels of the three factors, they cannot contribute to the degrees of freedom used to test the fixed factors of special interest (Status and Year). Therefore, as the dependent variable for the 16 combinations of Zone, Year, and Status, we summed the

number of individuals of the selected species in all the quadrats, standardized the sum to 20 quadrats (because in 2007 some sites had more and one had less than 20 quadrats), and calculated the $\log_{10}(\text{standardized sum} + 1)$. This design provides tests for the three terms of the 2 x 2 factorial combination of Year and Status each with 1 and 9 df with a critical of $F_{0.05, 1, 9 \text{ df}} = 5.12$. The power of this design could be increased by having more than 9 df in the denominator of the F ratio, which could be achieved by having more levels of Zone, or more levels of Year, or both, because this df is the product of the df for Zone (3) and the sum of the df for 2 x 2 factorial treatment combinations (1+1+1). A critical value of F of 4.00, sometimes used as a guide to a powerful test, would need 60 df. This could be done by having 21 pairs of sites inside and outside sanctuary zones with the present design of 2 levels each of Year and Status.

In analyses of variance in which there are tests of terms in the model which have 1 df for the term in the numerator (i.e., for factors with only two levels, or for combinations of factors with two levels), Pearson's correlation coefficient, r , can be used as a standardized measure of effect size or strength of an experimental effect, because in this use, called point-biserial correlation, it ranges from 0 to 1 (Field 2005). For the F-ratio as the test statistic,

$r = \sqrt{([F_{1, \text{df}}] / [F_{1, \text{df}} + \text{df}_{\text{den}}])}$ where $F_{1, \text{df}}$ is the F-ratio for the effect of a term with 1 df, and df_{den} is the degrees of freedom for the term used as denominator in the F-ratio. The interpretation of r in this context is straightforward because a correlation coefficient of 0.0 means no effect and larger values mean greater effect (although the relationship is not linear but increases as r^2) (Field 2005). One convention is that $r = 0.10$ is a small effect, $r = 0.30$ is a medium effect and $r = 0.50$ is a large effect (explaining 25% of the total variance).

Results

Even though the 15 species were among the most abundant in our samples, species 9, *Clypeomorus batillariaeformis*, occurred at only three sites. In contrast, species 2, the suspension feeding *Septifer bilocularis*, and species 15, the predator *Morula uva*, occurred at all 18 sites (Table 2). Similarly, individual sites had between eight species at sites H, P, and R (Mandu South Cobble, Gnarraloo Bay In, and Three Mile Out 1), and 13 species at site E (Jurabi Out 1). Of the $18 \times 15 = 270$ site by species combinations, only 187 or 69% occurred, emphasizing how different the assemblages of species at each site were, and providing one measure of spatial variation.

Spatial and temporal variation

Figure 1 provides a quick visual representation of spatial and temporal variation among species, the 18 sites, and the two years, although comparisons among the three sets of five species must be done in the light of the different scales for Mean $\log(\text{Number} + 1)$ on the vertical axes. Some species, such as *Tectus pyramis* and *Turbo haynesi*, appeared to be more abundant in 2007 than 2009, and *Septifer bilocularis* and *Serpulorbis* cf *sipho* the reverse. However, such appearances must be judged against the formal analyses of variances shown in Table 3, and in these the feature that stands out most is that 10 of the 15 species show statistical significance for the Year x Site term, indicating that whether the abundance was greater in 2007 or 2009 depended on which site was considered, or that temporal variation depended on what place was considered. This important interaction between Year and Site makes simple interpretation of the effects of Year or Site alone more complicated.

Statistically significant effects of Year occurred for five species with greater abundance in 2007 and three species with greater abundance in 2009, but all eight species also had interactions between Year and Site, so the sets of means need close examination. Statistically significant effects of Site occurred in all species except *Clypeomorus batillariaeformis*, but 10 of the 14 species also had interactions between Year and Site, so there were many

inconsistencies in space with time. Overall, more than half the places where species had the highest abundances involved only four sites, B, L, F and P (Mangrove Bay, Bateman Bay In, Jurabi In 1, and Gnarraloo Bay In 1) (Figure 1).

One way of helping judge the importance of the heterogeneities due to Year and Site and their interaction is the magnitude of effect, and the four values for each species sum to 100% (Table 3). Negative values occur when the F-ratio is less than one, and these should be considered to be 0%. For all except *Brachidontes ustulatus* and *Septifer bilocularis*, the magnitude of effect is largest for the residual term, that is, variation among quadrats within the Year x Site combinations. However, it is the terms associated with the fixed factors Year and Site that are important in assessing the spatial and temporal variations for these species, and one consistent pattern is obvious. The magnitude of effect is largest by manyfold for Site in all species except *Clypeomorus batillariaeformis* and *Tectus pyramis*. Similarly, the magnitude of effect is larger for the Year x Site interaction than for Year, again emphasizing that the effect of time depends on place.

Sanctuary Zones

Of the 15 selected species, only seven occurred regularly in the four pairs of sites inside and outside of the four sanctuary zones; the results of the analyses of variance are shown in Table 4. In these analyses, Zone and Residual represent random factors, and their variance components are given in the table. In the analyses for three of seven species, Zone has a larger variance component than the Residual, and has a statistically significant effect, indicating large spatial heterogeneity in the abundances among the four Zones, which are obvious from the means reported in their transformed and back-transformed values in Table 4.

The Year x Status factorial design is one which would have the potential to demonstrate the success of Sanctuary Zones in enhancing abundance of targeted species, by densities being higher In rather than Out, or by an interaction between Status and Year with abundances declining more in Out than in In over time, or abundances increasing more in In than in Out

over time. None of the seven species analyzed in Table 4 showed statistical significance for the interaction between Year and Status, and only one, *Serpulorbis*, had statistically different abundances in the two levels of Status with In exceeding Out.

Another value of these analyses of variance is that they permit calculation of effect size, r , shown in the last column of Table 4. Judged against convention, all values except for Status for *Serpulorbis* ($r = 0.162$) represent small effects. The relative values for r are greatest for Year x Status for *Morula uva* and *Tridacna maxima*, for Year for *Cronia. avellana* and *Septifer bilocularis*, and for Status for the other three species.

Discussion

The most important feature of the abundances of these 15 species of macroinvertebrates on rocky intertidal platforms at Ningaloo Marine Park is the pervasive spatial variability. Spatial variability at a regional scale was obvious among the four sanctuary zones for three of the seven species analysed because the variance component exceeded 50% and the Zone term was statistically significant. However, the variance component ranged from 15 to 30 % in the other four, thus adding substantial variation over that present within the sites among the quadrats (Table 4). Large-scale spatial variability was also obvious among sites in general because the magnitude of effect was greatest for Site for 14 of the 15 species when compared with the magnitude of effect for Year and Year x Site, with highest values ranging from 36 - 70 % in six species and lowest values ranging from 15 to 1% in six others (Table 3). Spatial variability at this scale, therefore, could be large, but was not universal, and depended on the species considered. Spatial variation was very much less between adjacent sites as judged by the small effect size of Status (Table 4). However, this would be an expected result if the platforms at adjacent sites were matched in physical attributes, as we attempted to do.

Temporal variability between 2007 and 2009 was very much less than spatial variability. The magnitude of effect associated with Year in Table 3 ranged from 0 to only 5.4%. The two species with the highest values, *Tectus pyramis* and *Turbo haynesi*, were both encountered,

mainly in 2007, as small, newly-recruited individuals at 9 and 12 sites respectively. Perhaps this temporal variability reflects variation in the abundance of cohorts of recruits that do not survive well on the platforms. The species with no temporal variability were *Echinometra mathaei*, *Conus sponsalis*, and *Morula uva*. The sea urchin is known to have sporadic recruitment and long-lived adults (Ebert Ecological Monographs 1982), so this might explain our observations of exclusively adult urchins with little variation between years. The two gastropods belong to groups that can live for several to many years.

Judging temporal variability by the effect sizes associated with Year in Tables 3 and 4 provides the same view of temporal variability as the magnitude of effects. The effect sizes in the analyses of the seven species at the eight sites inside and outside sanctuary zones were tiny, the largest only 0.081, and thus explaining only 0.66% of the variation. The effect sizes for these seven species were larger in the analyses of all the sites, ranging from 0.011 to 0.187, but these are still small effects by conventional standards. The other eight species had effect sizes of 0.003 to 0.284, the largest approaching a “medium” effect size. In fact, for the 15 species in Table 3 the magnitude of effect is highly positively correlated with (effect size)², so these measures provide almost identical views of temporal variability.

These evaluations of spatial and temporal variability suffer from the same difficulty because in almost all the analyses there were statistically important interactions between places and time, meaning that there are extra additive effects of the individual combinations of levels of the factors associated with space and time over and above the main effects of the levels of space and time. However, given the dominating size of the spatial variability in most cases, the influence of the extra variability due to the interaction would be relatively small.

There are some logical reasons why spatial variability far exceeded temporal variability in these data. The first is that the number of sites is so much greater than the two times; there was much more opportunity to find spatial variation. The second, related reason is that the two years are close together, and the processes that produce temporal variation, variations in recruitment and mortality with time, did not had long to act. Related to this is the dependence on life history characteristics of individual species in determining their the population

dynamics, the frequency and extent of numerical changes. Some species, such as *Echinometra mathaei* (Ebert Ecol Monogr) and *Tridacna maxima* (Chapter 9), are known to be long-lived, so their populations show inertia, changing little from year to year, unless they experience catastrophic conditions. Many gastropods have life-spans of several years, and few species on the platforms would have annual life cycles. One suggestion about judging whether populations are stable over time has been to observe populations long enough that there is a complete turn-over of individuals in it (Connell and Sousa find stability reference). By this criterion, studies such as ours, or continuing monitoring schemes, probably need to involve 5 to 10 or more years.

Acknowledgements

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Table 1. Taxonomic details of the 15 species

Phylum	Group	Family	Species
Cnidaria	Hard coral	Poritidae	<i>Porites</i> sp.
Echinodermata	Sea urchin	Echinometridae	<i>Echinometra mathaei</i> (Blainville, 1825)
Mollusca	Bivalve	Mytilidae	<i>Brachidontes ustulatus</i> (Lamarck, 1819)
			<i>Septifer bilocularis</i> (Linnaeus, 1758)
		Tridacnidae	<i>Tridacna maxima</i> (Röding, 1798)
	Gastropod	Turbinidae	<i>Turbo haynesi</i> Preston, 1914
		Trochidae	<i>Tectus pyramis</i> (Born, 1778)
		Cerithiidae	<i>Cerithium zonatum</i> (Wood, 1828)
			<i>Clypeomorus batillariaeformis</i> Habe & Kosuge, 1966
			<i>Rhinoclavis echinatum</i> Lamarck, 1822
		Strombidae	<i>Strombus mutabilis</i> Swainson, 1821
		Vermitidae	<i>Serpulorbis</i> cf <i>sipho</i>
		Thaididae	<i>Cronia avellana</i> (Reeve, 1846)
			<i>Morula uva</i> (Röding, 1798)
		Conidae	<i>Conus sponsalis</i> Hwass in Bruguiere, 1792

Table 2. Sites and occurrence of species sampled in August 2001 and July and September 2009.

Site Code	Site	Species code	Species in same order as in Figure 1.
A	Mildura Wreck	1	<i>Brachidontes ustulatus</i> (Lamarck, 1819)
B	Mildura Wreck West	2	<i>Septifer bilocularis</i> (Linnaeus, 1758)
C	Surfers North	3	<i>Serpulorbis</i> cf <i>sipho</i>
D	Surfers South	4	<i>Echinometra mathaei</i> (Blainville, 1825)
E	Jurabi Out 1	5	<i>Strombus mutabilis</i> Swainson, 1821
F	Jurabi In 1	6	<i>Cronia avellana</i> (Reeve, 1846)
G	Mangrove Bay	7	<i>Rhinoclavis echinatum</i> Lamarck, 1822
H	Madu South Cobble	8	<i>Conus sponsalis</i> Hwass in Bruguiere, 1792 <i>Clypeomorus batillariaeformis</i> Habe & Kosuge, 1966
I	Madu South Flat	9	
J	Pilgramunna	10	<i>Tectus pyramis</i> (Born, 1778)
K	Bateman Bay Out 1	11	<i>Turbo haynesi</i> Preston, 1914
L	Bateman Bay In	12	<i>Cerithium zonatum</i> (Wood, 1828)
M	Coral Bay North	13	<i>Tridacna maxima</i> (Roding, 1798)
N	Coral Bay South	14	<i>Porites</i> sp.
O	Gnarraloo Bay Out 1	15	<i>Morula uva</i> (Roding, 1798)
P	Gnarraloo Bay In 1		
Q	Three Mile In 1		
R	Three Mile Out 1		

Code	N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Species
A	60	1	1	1	0	1	1	1	1	0	0	1	0	1	1	1	11
B	30	0	1	1	1	1	1	1	1	0	0	0	0	1	1	1	10
C	55	1	1	1	1	1	1	1	1	0	1	0	0	1	1	1	12
D	60	0	1	1	1	1	1	1	1	0	1	0	0	1	1	1	11
E	40	1	1	1	1	1	1	1	1	0	1	1	0	1	1	1	13
F	40	0	1	1	1	1	1	1	1	0	1	1	0	1	1	1	12
G	40	0	1	1	1	1	1	1	0	1	1	1	1	0	0	1	11
H	40	1	1	1	0	0	1	1	0	1	0	1	0	0	0	1	8
I	40	0	1	1	1	1	0	1	1	0	0	1	0	1	0	1	9
J	50	1	1	1	1	1	1	1	1	0	0	1	0	1	0	1	11
K	51	0	1	0	0	1	1	1	0	1	1	1	1	1	0	1	10
L	50	0	1	1	1	1	1	1	1	0	1	1	1	1	0	1	12
M	50	1	1	1	1	1	1	1	0	0	0	1	1	1	0	1	11
N	49	1	1	1	1	1	1	1	1	0	0	1	1	1	0	1	12
O	37	0	1	1	1	1	1	0	1	0	1	0	0	1	0	1	9
P	40	0	1	1	1	1	1	0	0	0	0	1	0	1	0	1	8
Q	40	0	1	1	1	1	1	0	0	0	1	0	0	1	1	1	9
R	40	0	1	1	1	1	1	0	1	0	0	0	0	1	0	1	8
Sites		7	18	17	15	17	17	14	12	3	9	12	5	16	7	18	187

Table 3. Analyses of variance of $\log_{10}(\text{Number m}^{-2} + 1)$ of 15 species.

a) matches first panel of graphs

Brachidontes ustulus: 7 Sites; Effect size for Year $r = 0.093$

Source	df	MS	F Ratio	Prob > F	ω^2 (%)
Year	1	0.4416	2.84	0.0924	0.2
Site	6	21.7689	140.41	<.0001	70.3
Year*Site	6	0.3361	2.160	0.0457	0.3
Residual	330	0.1550			28.93

Septifer bilocularis: 18 sites; Effect size for Year $r = 0.174$

Source	df	MS	F Ratio	Prob > F	ω^2 (%)
Year	1	1.18274	23.7451	<.0001	1.1
Site	17	2.9473	59.1712	<.0001	49.5
Year*Site	17	0.55595	11.1614	<.0001	8.7
Residual	776	0.04981			40.7

Serpulorbis cf siphon: 17 sites; Effect size for Year $r = 0.187$

Source	df	MS	F Ratio	Prob > F	ω^2 (%)
Year	1	1.53482	26.0305	<.0001	1.6
Site	16	2.11493	35.8692	<.0001	36.0
Year*Site	16	0.82503	13.9925	<.0001	13.4
Residual	727	0.05896			49.0

Echinometra mathaei: 15 sites; Effect size for Year $r = 0.011$

Source	df	MS	F Ratio	Prob > F	ω^2 (%)
Year	1	0.00362	0.0804	0.7768	-0.1
Site	14	1.94273	43.1053	<.0001	44.1
Year*Site	14	0.02085	0.4626	0.9521	-0.6
Residual	631	0.04507			56.6

Strombus mutabilis: 17 sites; Effect size for Year $r = 0.105$

Source	df	MS	F Ratio	Prob > F	ω^2 (%)
Year	1	0.52765	8.2959	0.0041	0.5
Site	16	2.3054	36.2466	<.0001	38.1
Year*Site	16	0.61283	9.6353	<.0001	9.3
Residual	738	0.06360			52.1

Table 3 continued matches second panel

Cronia avellana: 17 sites; Effect size for Year $r = 0.138$

Source	df	MS	F Ratio	Prob > F	ω^2 (%)
Year	1	0.74035	14.3643	0.0002	1.0
Site	16	1.70884	33.1550	<.0001	39.1
Year*Site	16	0.10143	1.9679	0.0130	1.2
Residual	738	0.051541			58.7

Rhinoclavis echinatum: 14 sites; Effect size for Year $r = 0.154$

Source	df	MS	F Ratio	Prob > F	ω^2 (%)
Year	1	0.36742	15.2125	0.0001	1.4
Site	13	0.57749	23.9103	<.0001	29.4
Year*Site	13	0.10755	4.4530	<.0001	4.4
Residual	627	0.024152			64.7

Conus sponsalis: 12 sites; Effect size for Year $r = 0.003$

Source	df	MS	F Ratio	Prob > F	ω^2 (%)
Year	1	0.00014	0.0040	0.9497	-0.1
Site	11	0.55559	15.7539	<.0001	22.5
Year*Site	11	0.06449	1.8287	0.0466	1.3
Residual	527	0.035266			76.4

Clypeomorus batillariaeformis : 3 sites; Effect size for Year $r = 0.135$

Source	df	MS	F Ratio	Prob > F	ω^2 (%)
Year	1	0.71634	2.3259	0.1298	1.0
Site	2	0.50282	1.6326	0.1996	0.9
Year*Site	2	0.6319	2.0517	0.1328	1.6
Residual	125	0.307988			96.5

Tectus pyramis: 9 sites; Effect size for Year $r = 0.282$

Source	df	MS	F Ratio	Prob > F	ω^2 (%)
Year	1	0.47009	34.1986	<.0001	5.4
Site	8	0.17215	12.5238	<.0001	14.9
Year*Site	8	0.14901	10.8399	<.0001	12.8
Residual	395	0.013746			66.9

Table 3 concluded: matches third panel of graphs.

Turbo hanesi: 12 sites; Effect size for Year $r = 0.245$

Source	df	MS	F Ratio	Prob > F	ω^2 (%)
Year	1	0.82788	33.7166	<.0001	3.9
Site	11	0.45855	18.6751	<.0001	23.4
Year*Site	11	0.14392	5.8612	<.0001	6.4
Residual	526	0.024554			66.2

Cerithium zonatus: 5 sites; Effect size for Year $r = 0.102$

Source	df	MS	F Ratio	Prob > F	ω^2 (%)
Year	1	0.16433	2.4236	0.1209	0.5
Site	4	0.41964	6.1890	<.0001	7.8
Year*Site	4	0.13115	1.9343	0.1056	1.4
Residual	230	0.067803			90.3

Tridacna maxima: 16 sites; Effect size for Year $r = 0.114$

Source	df	MS	F Ratio	Prob > F	ω^2 (%)
Year	1	0.20265	9.1571	0.0026	0.9
Site	15	0.20306	9.1755	<.0001	13.6
Year*Site	15	0.08064	3.6438	<.0001	4.4
Residual	700	0.022130			81.1

Porites sp.: 7 sites; Effect size for Year $r = 0.092$

Source	df	MS	F Ratio	Prob > F	ω^2 (%)
Year	1	0.03497	2.6531	0.1044	0.5
Site	6	0.12343	9.3638	<.0001	13.3
Year*Site	6	0.01388	1.0532	0.3909	0.1
Residual	311	0.013182			86.2

Morula uva: 18 sites; Effect size for Year $r = 0.026$

Source	df	MS	F Ratio	Prob > F	ω^2 (%)
Year	1	0.00826	0.5379	0.4635	-0.1
Site	17	0.06204	4.0403	<.0001	5.91
Year*Site	17	0.022	1.4326	0.1138	0.81
Residual	776	0.015355			93.3

Table 4. Analyses of variance for Zone x Year x Status of the log₁₀(standardized number in 20 1-m² quadrats+1) Variance components as % are shown for the random terms in the model. Means for the levels the statistically significant terms are given.

Cronia avellana

Source	df	MS	F Ratio	Prob > F	% variance component	Effect size r
Zone	3	0.84097	6.7271	0.0112	58.878	
Year	1	0.27479	2.1981	0.1723		0.081
Status	1	0.00172	0.0138	0.9092		0.006
Year*Status	1	0.11064	0.8850	0.3714		0.052
Residual	9	0.12501			41.122	
Means		Jurabi	Bateman	Gnarraloo	Three Mile	
log(X+1)		1.48	1.50	1.60	0.61 ± 0.176	
X		29.2	30.6	38.8	3.1	

Echinometra mathaei

Source	df	MS	F Ratio	Prob > F	% variance component	Effect size r
Zone	3	1.36295	2.6743	0.1105	29.506	
Year	1	0.01036	0.0203	0.8898		0.005
Status	1	0.87805	1.7228	0.2218		0.047
Year*Status	1	0.21792	0.4276	0.5295		0.023
Residual	9	0.50966			70.494	

Morula uva

Source	df	MS	F Ratio	Prob > F	% variance component	Effect size r
Zone	3	0.14202	1.6838	0.2392	14.599	
Year	1	0.12199	1.4463	0.2598		0.045
Status	1	0.00475	0.0563	0.8177		0.009
Year*Status	1	0.20764	2.4618	0.1511		0.058
Residual	9	0.08435			85.401	

continued

Septifer bilocularis

Source	df	MS	F Ratio	Prob > F	% variance component	Effect size r
Zone	3	2.24311	6.9212	0.0103	59.682	
Year	1	0.21793	0.6724	0.4334		0.030
Status	1	0.00587	0.0181	0.8959		0.005
Year*Status	1	0.0642	0.1981	0.6668		0.016
Residual	9	0.32409			40.318	
Means		Jurabi	Bateman	Gnarraloo	Three Mile	
log(X+1)		1.19	1.31	0.43	2.26 ± 0.285	
X		14.5	19.4	1.7	181.0	

Serpulorbis cf siphon

Source	df	MS	F Ratio	Prob > F	% variance component	Effect size r
Zone	3	0.66772	2.1586	0.1628	22.460	
Year	1	0.28893	0.9341	0.3591		0.036
Status	1	6.15718	19.9048	0.0016		0.162
Year*Status	1	0.27328	0.8835	0.3718		0.035
Residual	9	0.30933			77.540	
Means				In	Out	
log(X+1)				1.66	0.41 ± 0.197	
X				44.7	1.6	

Strombus mutabilis

Source	df	MS	F Ratio	Prob > F	% variance component	Effect size r
Zone	3	2.06508	7.6479	0.0076	62.434	
Year	1	0.06051	0.2241	0.6472		0.019
Status	1	0.697	2.5813	0.1426		0.064
Year*Status	1	0.01605	0.0594	0.8129		0.010
Residual	9	0.27002			37.566	
Means		Jurabi	Bateman	Gnarraloo	Three Mile	
log(X+1)		1.67	1.77	0.87	0.25 ± 0.250	
X		45.8	57.9	7.4	0.8	

continued

Tridacna maxima

Source	df	MS	F Ratio	Prob > F	% variance component	Effect size r
Zone	3	0.49695	1.9254	0.1960	18.789	
Year	1	0.05841	0.2263	0.6456		0.018
Status	1	0.00283	0.0110	0.9188		0.004
Year*Status	1	0.22005	0.8526	0.3799		0.034
Residual	9	0.25809			81.211	

concluded

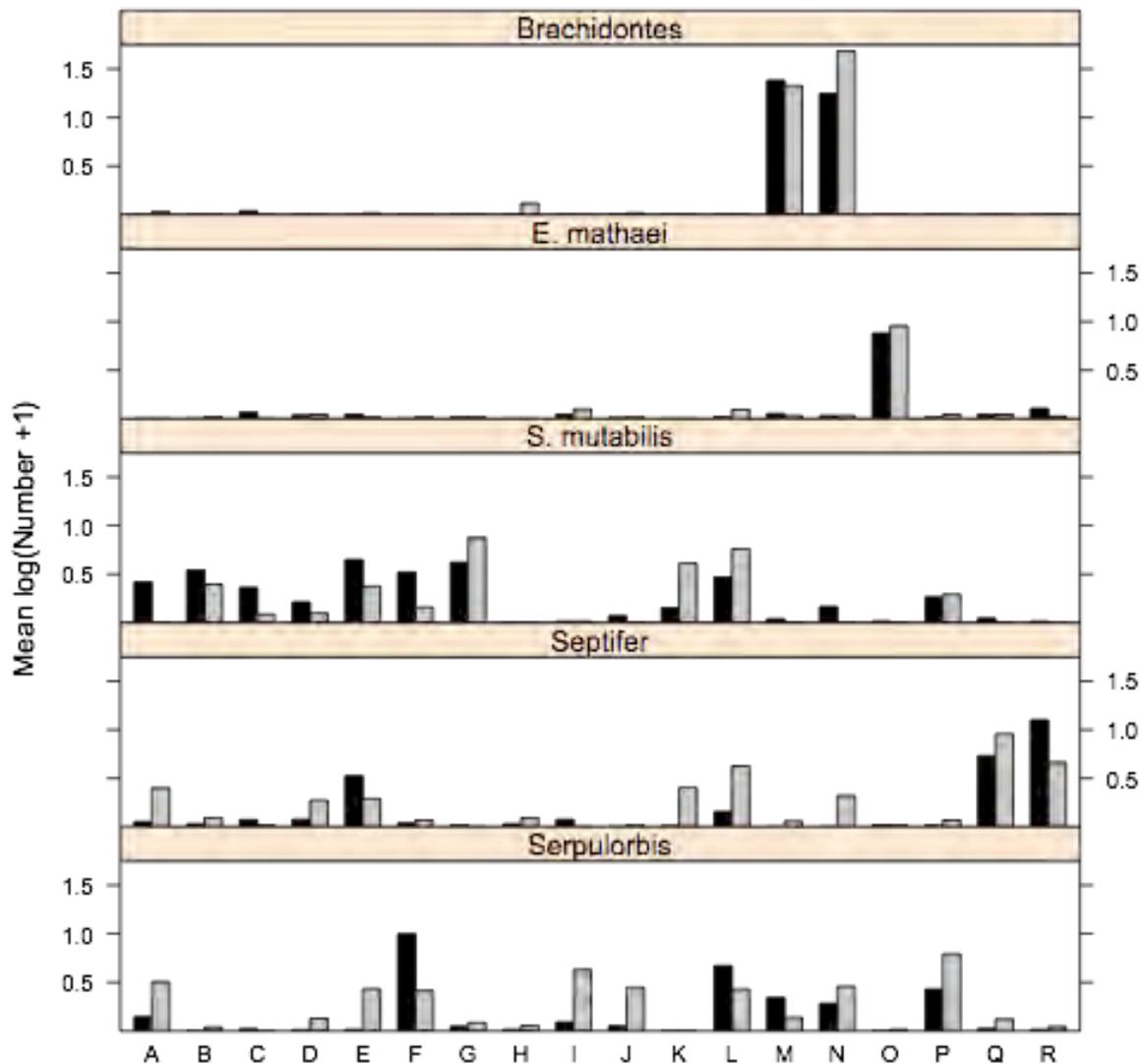


Figure 1. Means of $\log_{10}(\text{Number} + 1)$ of selected species at 18 sites (coded A to R from north to south - see Table 2) in August 2007 (black bars) and July and September 2009 (grey bars). Sites and times with no visible bars indicate absence of the species. 1.5 on the Y-axis is equivalent to 30.6 individuals m^{-2} . Common standard error for sample size of 20 quadrats for the species are:

<i>Brachidontes</i>	0.088
<i>E.mathaei</i>	0.047
<i>S. mutabilis</i>	0.056
<i>Septifer</i>	0.050
<i>Serppulorbis</i>	0.054

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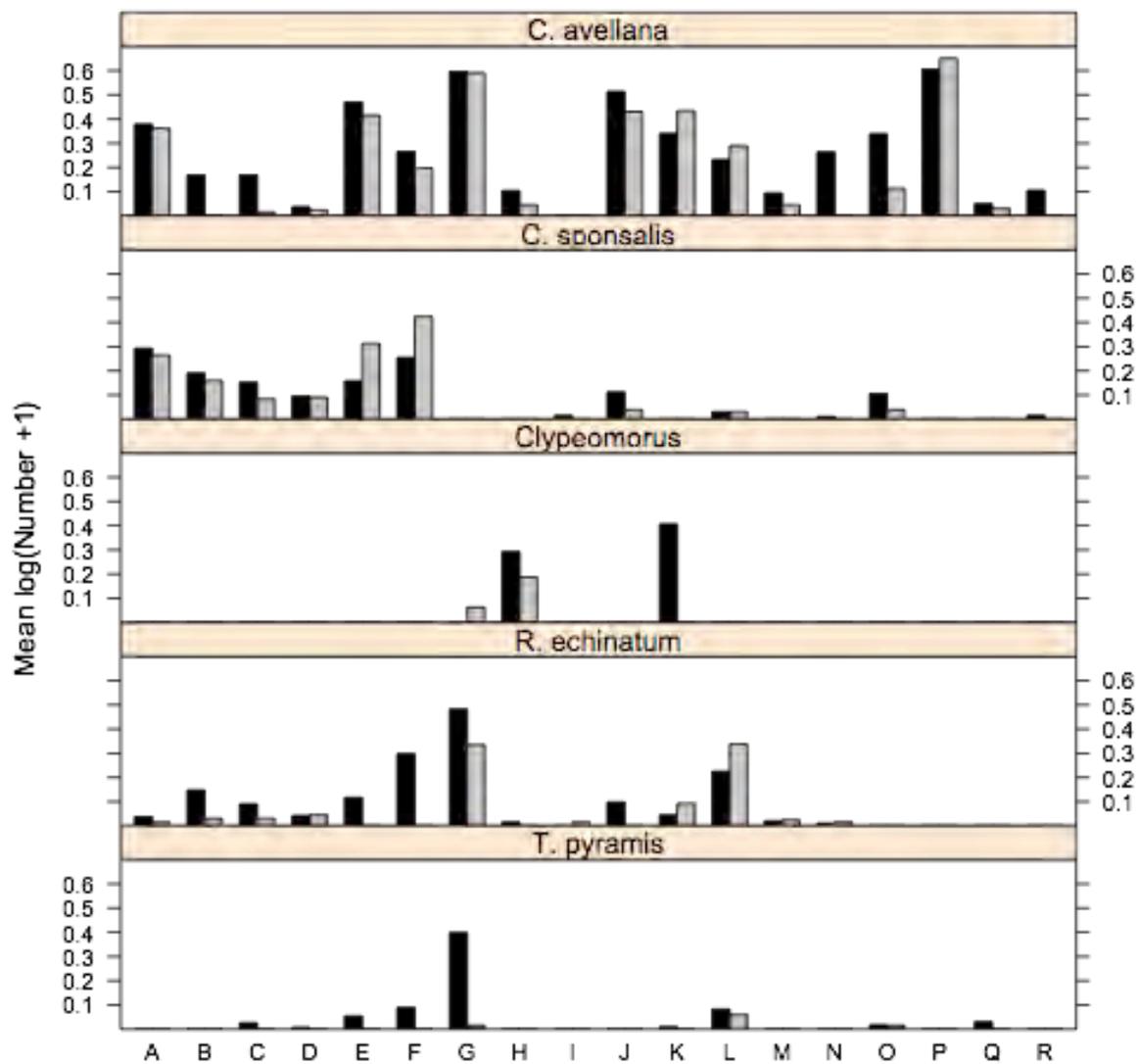


Figure 1 continued - see caption on previous page. 0.6 on Y-axis is equivalent to 3 individuals m^{-2} . Common standard error for sample size of 20 quadrats for the species are:

<i>C. avellana</i>	0.058
<i>C. sponsalis</i>	0.042
<i>Clypeomorus</i>	0.124
<i>R. echinatum</i>	0.035
<i>T. pyramis</i>	0.026

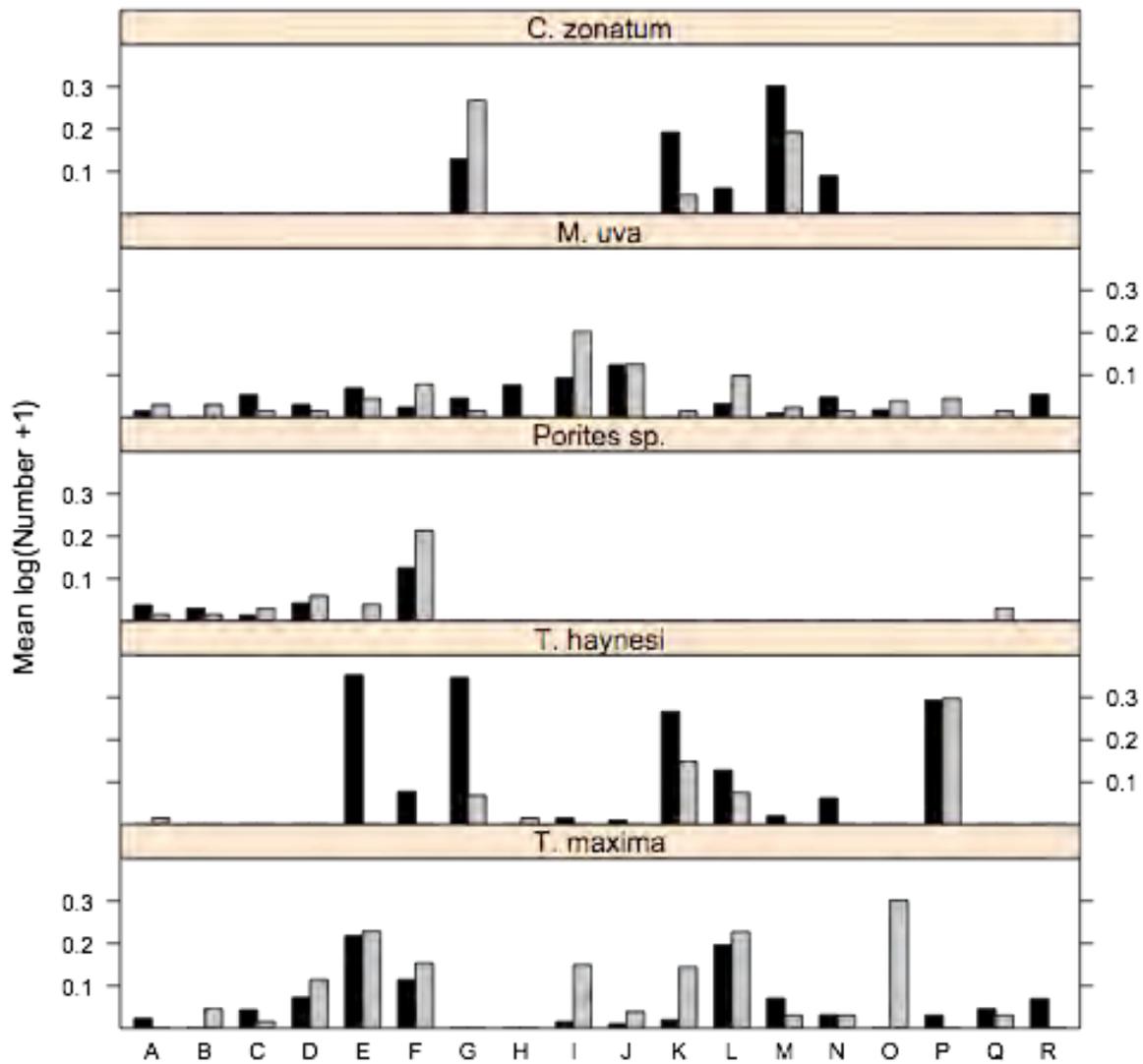


Figure 1 concluded. -see two pages previously for complete caption. 0.3 on the Y-axis is equivalent to 0.99 individuals m^{-2} . Common standard error for sample size of 20 quadrats for the species are:

<i>C. zonatum</i>	0.058
<i>M. uva</i>	0.028
<i>Porites sp.</i>	0.026
<i>T. haynesi</i>	0.035
<i>T. maxima</i>	0.033

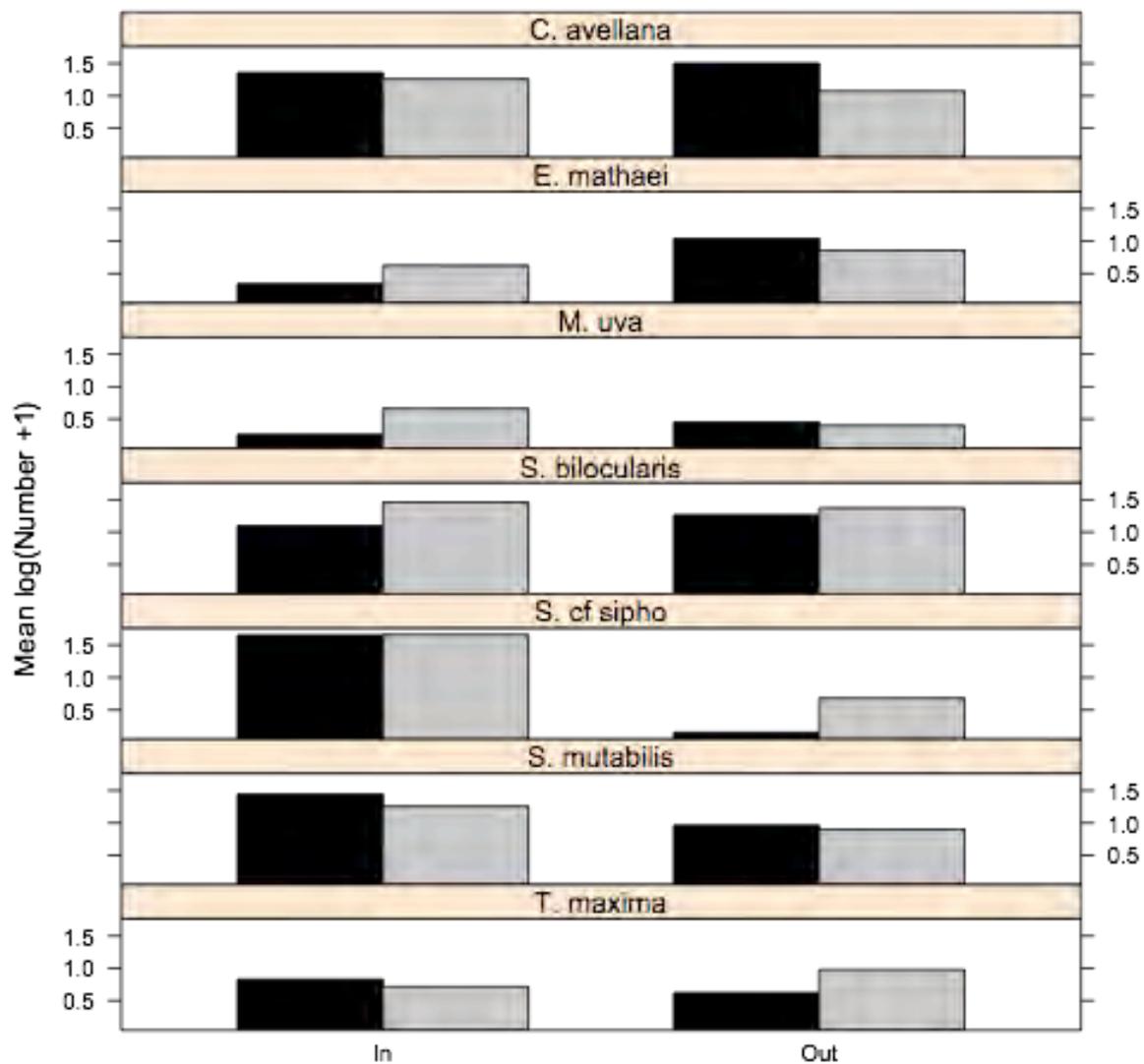


Figure 2. Mean of $\log(\text{Number in } 20 \text{ m}^2 + 1)$ of seven species inside (In) or outside (Out) four Sanctuary Zones in August 2007 (black bars) and July or September 2009 (grey bars). Backtransformed values on the Y axis for 0.5, 1.0 and 1.5 are 2.2, 9.0, and 30.6 individuals 20-m^{-2} . Analyses of variance are in Table 4. The common standard errors for the four treatment for each species are:

<i>C. avellana</i>	0.177
<i>E. mathaei</i>	0.357
<i>M. uva</i>	0.145
<i>S. bilocularis</i>	0.285
<i>S. cf sipho</i>	0.278
<i>S. mutabilis</i>	0.260
<i>T. maxima</i>	0.254

**Chapter 6: Spatial and temporal
variability in assemblages of intertidal
invertebrate species in the Ningaloo
Marine Park, 2007-2009**

Introduction

The ability to detect differences among sites or among sites of particular categories or to detect changes over time depends on how much variation there is from place to place and from one time to another. As outlined in Chapter 1, our sampling scheme focused on the assemblages of animals on rocky intertidal platforms in Ningaloo Marine Park as a whole, rather than as a set of individual focal species. Our samples of the assemblages of animals represent the ecological community on the platforms which are an easily delineated habitat. Chapter 2 broached some of the topics associated with community ecology: species richness, diversity, dominance, relative abundance, and trophic structure, but did not tackle all the issues about the composition of the assemblages of animals where the identity and abundance of all the species are considered simultaneously. Here we present some multivariate analyses describing the spatial and temporal differences in the composition of the assemblages.

Methods

The data used in this chapter were the sums of the numbers of each species found in the replicate 1-m² quadrats taken at each site each time it was sampled in 2007 (18 sites in north and south), 2008 (8 sites in the north) and 2009 (32 sites in the north and south of the Park), adjusted to be equivalent to 20 quadrats for those sites and times when fewer or more than 20 quadrats made up the sample (see Research Chapter 3, Table 2 -2008 and 2009 had 20 quadrats per site, so number in 2007 can be calculated). The schedule of sites and times is shown in detail in Research Chapter 1, Table 1. These raw numbers were transformed using the $\log_{10}(x+1)$ transformation to reduce the influence of species that had high abundances (see Research Chapter 2, Table 1 for a listing of the species and their overall abundance in the samples).

We used various subsets of these data to answer our questions about spatial and temporal variability of the assemblages of macroinvertebrates using the software Primer E (Clarke and Gorley 2006) and the PERMANOVA+ add-on (Anderson et al. 2008). To provide

descriptive, visual summaries of the differences among the assemblages at different sites and different sites at different times, we used ordination by non-metric multidimensional scaling (nMDS) of the Bray Curtis similarity matrix calculated from abundances of all the species in our samples where the entries for the matrix are:

$$S_{jk} = 100 \left\{ 1 - \frac{(\sum |x_{ij} - x_{ik}| / \sum (x_{ij} + x_{ik}))}{2} \right\}$$

for all i species in samples j and k , with $x \equiv \log_{10}(x+1)$.

We performed separate analyses for the 2007 data alone, the 2009 data alone, the 2007, 2008, 2009 data combined, and the subset of 18 sites sampled both in 2007 and 2009. To emphasize particular features of these ordinations, sites were identified on the basic figures according to a number of categories or their combinations:

- i) year of sampling (levels of Date, 2007, 2008, 2009);
- ii) North or South in the Park (boundary is between Yardie Creek and Bateman Bay Out 2);
- iii) Sanctuary Zone (including sites outside each zone, but close to them - see Research Chapter 1, Table 2); and
- iv) Status (In (a Sanctuary Zone), Out (in a Recreation Zone), SP (in a Special Purpose Area), or Off shore (inshore from a Sanctuary Zone that does not reach the beach) (Table 1).

For formal statistical tests of hypotheses about the comparisons between levels of i) and levels of ii) and iii) mentioned above, we used the permutational multivariate analysis of variance procedures implemented by PERMANOVA+ in the Primer E software. These tested the influence of year of sampling (Date, 2007 or 2009) and large geographic Region (North or South), or Date and smaller geographic Region (the nine sanctuary zones) by a repeated measures analysis of the structure of the assemblages at the 18 sites sampled in both 2007 and 2009. To visualize the statistically significant interactions, as revealed by the permutational multivariate analyses of variance for comparisons iii) and iv) above, we performed a canonical analyses of principal co-ordinates (CAP in the jargon of Primer E see Anderson and Willis 2003). This analysis is the non-parametric distance based equivalent of a parametric discriminant analysis in that both attempt to separate *a priori* defined groups in multivariate space. The CAP ordination of the groups in the interaction term is in a way analogous to a univariate interaction plot.

Vector overlays on both nMDS and CAP ordinations visualised the relationships between the species in the data set and the ordination. The vector overlay consists of a circle with a radius of 1, whose relative size and position on the graph is arbitrary with respect to the underlying plot (Anderson *et al.* 2008). The length and direction of each vector within the circle represents the strength and sign respectively of the correlation between the species and the underlying ordination. We used Spearman Rank correlations as recommended by Anderson *et al.* (2008) as more appropriate and flexible as they do not require linear relationships between the individual species and the data cloud. For each graph, we restricted the vector display to the 10-12 species with the highest correlation coefficients. Note that this should be regarded as an exploratory tool only and cannot be interpreted as indicative of causation of either the effects of factors or of dissimilarities between sample points (Anderson *et al.* 2008).

Results

Spatial variation in composition of the assemblages of macroinvertebrates

In 2007 we sampled 18 sites, 10 in the north, and 8 in the south of the Park. The ordination shows some sites widely different from the others, with Mandu South Cobble and Flat separated from other northern sites in both dimensions of the plot. Similarly Three Mile In 1 and Out 1, geographically adjacent sites, and Gnarraloo Bay Out 1 differed a lot from the other southern sites (Figure 1). As judged by the orientation of the radiating lines of the vector overlay, abundance of a cone, *Conus sponsalis*, was positively correlated with sites to the right of the plot, which are mostly but not exclusively northern sites, while the abundance of the whelk *Thais orbita* was positively correlated with three of the most southern sites, Three Mile and a site at Gnarraloo Bay.

The comparable plot of the nMDS ordination for 2009 revealed the same kind of spatial variation as seen for 2007, but some details differed (Figure 2). The Three Mile and Gnarraloo Bay sites were again separated from the other southern sites, and were positively with the abundance of an urchin, *Echinometra mathaei*, a chiton, *Clavarizona hirtosa*, a whelk, *Thais orbita*, and a limpet, *Siphonaria* sp. Unlike the rough grouping of northern and southern sites in 2007, points in the middle of the plot for 2009 were a mixture of northern and southern sites, so there was no strong signal of drastic differences in species composition of the assemblages with these large-scale geographic regions within the Park in 2009.

Spatial and temporal variation

Including the data for all sites and all times they were sampled in a single analysis provides a view of spatial and temporal variation in the assemblages simultaneously (Figure 3). One feature stands out. The sites sampled two or three times differed as much as some pairs sites differed from each other. For example, Mildura Wreck was sampled in each year. Two of the years were close together in the plot (just above the vector for *Turbo haynesi*), while the third year was separated more (below the vector and intermixed with other northern sites). Similarly, the two points for Pilgramunna (P) are more widely separated in the plot than the four points for Mangrove Bay and Mangrove Point (MB and MP), a pair of sites separated by only 300 m. On the other hand, the two sites at Mandu South were about 100 m apart, but the Cobble differed considerably in the nature of the habitat because it was a boulder field rather than the rocky pavement of the Flat. In the ordination, the separation of each these sites in different years was considerably less than the separation of the two pairs of points in the plot (Figure 3).

A second feature of the plot was that although the northern and southern sites overlapped considerably in the bottom right of the plot, northern sites predominated at the top of the plot, and southern sites to the left, indicative of large differences in the assemblages (Figure 3). This suggests that this large-scale geographic pattern deserves additional analysis to which we return in another section.

A third aspect of this ordination shows up by coding the points according to the management status of the sites (Figure 4). The coding of the sites by Status clearly shows that the four categories are represented by sites that are intermixed. The exception is the southern-most sites, displayed on the left of the plot, namely Three Mile and Gnarraloo Bay, where there are no fully protected sanctuary zones or even special purpose zones, only offshore sanctuaries. This means that all rock platforms in this area are unprotected.

Statistical tests of spatial and temporal variation in composition of assemblages of macroinvertebrates

To formally test the influence of spatial and temporal variability, we used the subset of our data that provided a balanced data set, that is, the 18 sites that were sampled in both 2007 and 2009. The Bray Curtis similarity matrices for the 18 sites in 2007 and in 2009 were highly correlated ($r = 0.719$) as tested by a non-parametric equivalent of a Mantel test using Spearman Rank correlation (Clarke and Gorley 2006). Thus, the pattern of differences among the sites was roughly similar, but not identical, in each year. We performed two analyses, dividing the sites into groups at two geographic scales, a large-scale, dividing the sites into North and South (Region), and a medium-scale, dividing the sites into groups associated with nine of the sanctuary zones (Sanctuary). Because we sampled the same sites on each of two Dates, the design of the analysis is a repeated measures design, with Sites nested within Region or Sanctuary. The results of the two analyses are similar (Table 2). There was a statistically significant interaction between Date and Region, and Date and Sanctuary (both $p = 0.02$) indicating that the spatial differences in the assemblages of macroinvertebrates depended on which year was considered, and making straightforward interpretations about the two main effects complicated. However, because the statistical significances for the main effects had much lower probabilities, it is possible that there may be strong patterns for the main effects as well.

The square root of the the estimates of the components of variance shown in Table 2 help evaluate the relative influence of spatial and temporal variability. When space was considered at a large scale, spatial (Region) and temporal (Date) variability differ by a factor of 1.5 relative to each other and to their respective residual variability, and the variability associated with the interaction between space and time is somewhat less than for the lower value for time by itself. This pattern is repeated when spatial variability was considered at the scale of Sanctuary, but the factor by which spatial variability exceeded temporal variability was about 2.0.

To help visualize these differences, and to examine the nature of the interaction between spatial variability and temporal variability, we performed CAP ordination. The repeated measures analyses indicated an interaction between Date and Region, and these four treatment combinations are shown in the CAP ordination in Figure 5. The 2007 South group is separated on the horizontal axis from its 2009 group which is in line with both 2009 groups. The relative positions of the 2007 and 2009 categories on the vertical axis differ for North and South. Thus, the composition of the assemblages altered in different opposite ways by Region, according to which Date it was.

The CAP ordination is more complicated for the spatial scale of Sanctuary because of the larger number of levels, but evidence of the Date x Sanctuary effect of the multivariate permutational analysis of variance shows up in Figure 6. For example, the pair of sites associated with 3 Mile Sanctuary Zone, top left in Figure 6, are similar within years, but different between years. In contrast, the four sites in Lighthouse Sanctuary are tightly clustered within and between levels of Date near the centre of the plot, and the pair of sites associated with Bateman Bay Sanctuary are closely similar within years, and slightly more different between years.

Discussion

Spatial variation

When our samples of the assemblage of macroinvertebrates were used to estimate the entire community on the rocky intertidal platforms of Ningaloo Marine Park, the most apparent feature was that the assemblages varied immensely, at all spatial scales. Perhaps this should not be surprising because the sites we sampled spanned more than 2 degrees of latitude, included platforms with various structural features, and involved a fauna consisting of components with main distributional ranges were more tropical or more temperate (Research Chapter 2). Indeed, there was important heterogeneity at the large geographic scale between the 17 northern sites and the 16 southern sites. Furthermore, there were large differences at the smaller scale provided by the distances between 9 Sanctuary Zones. The implications of spatial variation at these large geographic scales is that future sampling should cover the entire Park, and not be restricted to particular sections. However, the spatial differences in assemblages of most concern for managers were the large differences that could occur between sites only metres or kilometres apart sometimes without immediately obvious reasons. This issue is addressed in other Research Chapters where we measured differences in physical features of the platforms and accounted for some of the variation in assemblages.

Temporal variation

The view of temporal variation that our study can provide is much more restricted than for spatial variation because of the short intervals between our sampling in 2007, 2008, and 2009. Many of the species in the assemblages are long-lived. For example, Research Chapter 4 estimated that the median age of the small giant clam, *Tridacna maxima*, could be 13 years. Sea urchins such as *Echinometra mathaei* reach considerable ages as can many gastropods (see discussion in Research Chapter 4). This means that populations of these species will have a great deal of inertia, and changes in their abundance from year to year will not be large, in the absence of some catastrophic event.

Despite the potential for temporal variation to be small, our formal statistical tests revealed significant interactions between space and time. Changes in assemblages between 2007 and

2009 differed depending on which Region or Sanctuary Zone was considered. So whatever the cause or causes of temporal change were, they were not consistent throughout the Park. This result is of interest in itself, and it provides another warning that future sampling needs to cover all parts of the Park.

This result also demonstrates that our methods of data collection and statistical analysis hold promise for future comparisons about the efficacy of management procedures related to sanctuary zones because, over time, assemblages enhanced by protection or disturbed by human impacts, would show this kind of statistical interaction between status (protected, not protected) and time.

Finally, the ordinations showing the sites coded by status show that the four categories are intermixed, so that the Sanctuary Zones and Special Purpose Areas cover the entire variety of assemblages in our sample of sites, with the notable exception that two southern sanctuaries, Gnarraloo Bay and 3 Mile, do not extend to shore. Furthermore, future sampling of the same sites will be able to determine any effect that the difference in the details of protection that these two levels of status have on assemblages of macroinvertebrates on rocky intertidal platforms that are so easily accessed by visitors.

References

- Anderson, M.J., Gorley, R.N. & Clarke, K.R. 2008. PERMANOVA+ for PRIMER: Guide to Software and Statistical Methods. PRIMER-E: Plymouth, UK.
- Anderson, M.J. & Willis, T.J. 2003. Canonical analysis of principal coordinates: a useful method of constrained ordination for ecology. *Ecology* 84: 511-525.
- Clarke, K.R. & Gorley, R.N. 2006. PRIMER v6: User manual/Tutorial. PRIMER-E Ltd, Plymouth, UK.

Table 1. Intertidal rocky platforms in Ningaloo Marine Park, listed in order from North to South, sampled for invertebrates in 1-m² quadrats. Sites are in Sanctuary Zones (*), Special Purpose Areas (**), inshore from offshore Sanctuary Zones (***), or in Recreational Zones (no symbol). The letters shown for each site are used as identifiers in the Figures.

Sites		Latitude S	Longitude E
Mildura Wreck**	MW	21°47'6.30"	114° 9'54.52"
Mildura Wreck West**	MWW	21°47'9.05"	114° 9'44.85"
Surfers North**	SN	21°47'13.05"	114° 9'35.84"
Surfers South**	SS	21°47'26.16"	114° 9'14.37"
Jurabi Out 2	J Out2	21°50'44.64"	114° 2'10.14"
Jurabi Out 1	J Out1	21°50'51.78"	114° 1'51.30"
Jurabi In 1**	J In1	21°50'57.63"	114° 1'33.43"
Jurabi In 2**	J In2	21°51'1.25"	114° 1'26.81"
Jurabi In 3**	J In3	21°51'6.13"	114° 1'21.89"
Mangrove Bay*	MB	21°57'40.88"	113°56'25.43"
Mangrove Point*	MP	21°57'50.14"	113°56'24.78"
Mandu South Cobble*	MS C	22° 8'43.16"	113°52'12.04"
Mandu South Flat*	MS F	22° 8'45.01"	113°52'11.25"
Pilgramunna	P	22°11'39.48"	113°51'17.38"
Yardie Creek North	YCN	22°19'36.17"	113°48'31.95"
Yardie Creek South	YCS	22°19'42.12"	113°48'29.52"
Bateman Bay Out 2	BB Out1	23° 2'17.90"	113°49'42.98"
Bateman Bay Out 1	BB Out2	23° 2'37.76"	113°49'39.20"
Bateman Bay In*	BB In	23° 2'58.41"	113°49'24.34"
Coral Bay South**	CBN	23° 9'24.01"	113°45'59.89"
Coral Bay North**	CBS	23° 9'11.32"	113°46'6.00"
Elles In**	E In	23°26'0.79"	113°46'52.76"
EllesOut	E Out	23°26'16.14"	113°46'48.08"
Gnaraloo Bay Out 2	GB Out2	23°45'36.72"	113°33'43.14"
Gnaraloo Bay Out 1	GB Out1	23°45'47.82"	113°33'30.24"
Gnaraloo Bay In 2***	GB In2	23°46'13.93"	113°32'15.93"
Gnaraloo Bay In 1***	GB In1	23°46'19.75"	113°32'10.30"
Three Mile North***	TM InN	23°52'13.51"	113°29'48.00"
Three Mile In 2***	TM In2	23°52'30.39"	113°29'40.80"
Three Mile In 1***	TM In1	23°52'32.00"	113°29'38.68"
Three Mile Out 1	TM Out1	23°52'33.00"	113°29'37.63"
Three Mile Out 2	TM Out2	23°52'45.54"	113°29'25.42"

Table 2. Repeated measures multivariate analyses of variance by 9999 permutations of the assemblages of macroinvertebrates at 18 sites each sampled in Dates, 2007 and 2009. Unique permutations indicates how many permutations are possible, given the structure of the data.

a. Analysis of two large-scale geographic Regions (North or South) on two Dates (2007 or 2009).

Source	df	MS	Pseudo-F	P(perm)	Unique permutations	Square root of estimates of components of variance
<i>Between sites</i>						
Region	1	7424.20	2.3200	0.0056	8905	15.14
Sites (Region)	16	3200.20	3.4858	0.0001	9792	33.78
<i>Within sites</i>						
Date	1	3953.60	4.3064	0.0003	9919	13.07
Date x Region	1	1836.90	2.0008	0.0242	9904	10.17
Residual	16	918.07				30.30

b. Analysis of nine medium-scale geographic Regions (nine Sanctuary Zones) on two Dates (2007 or 2009).

Source	df	MS	Pseudo-F	P(perm)	Unique permutations	Square root of estimates of components of variance
<i>Between sites</i>						
Sanctuary	8	5033.7	2.4679	0.0001	9843	27.65
Sites (Sanctuary)	9	2039.7	2.5951	0.0003	9871	25.04
<i>Within sites</i>						
Date	1	3368.6	4.2860	0.0039	9938	12.94
Date x Sanctuary	8	1181.5	1.5033	0.0218	9867	14.21
Residual	9	785.97				28.05

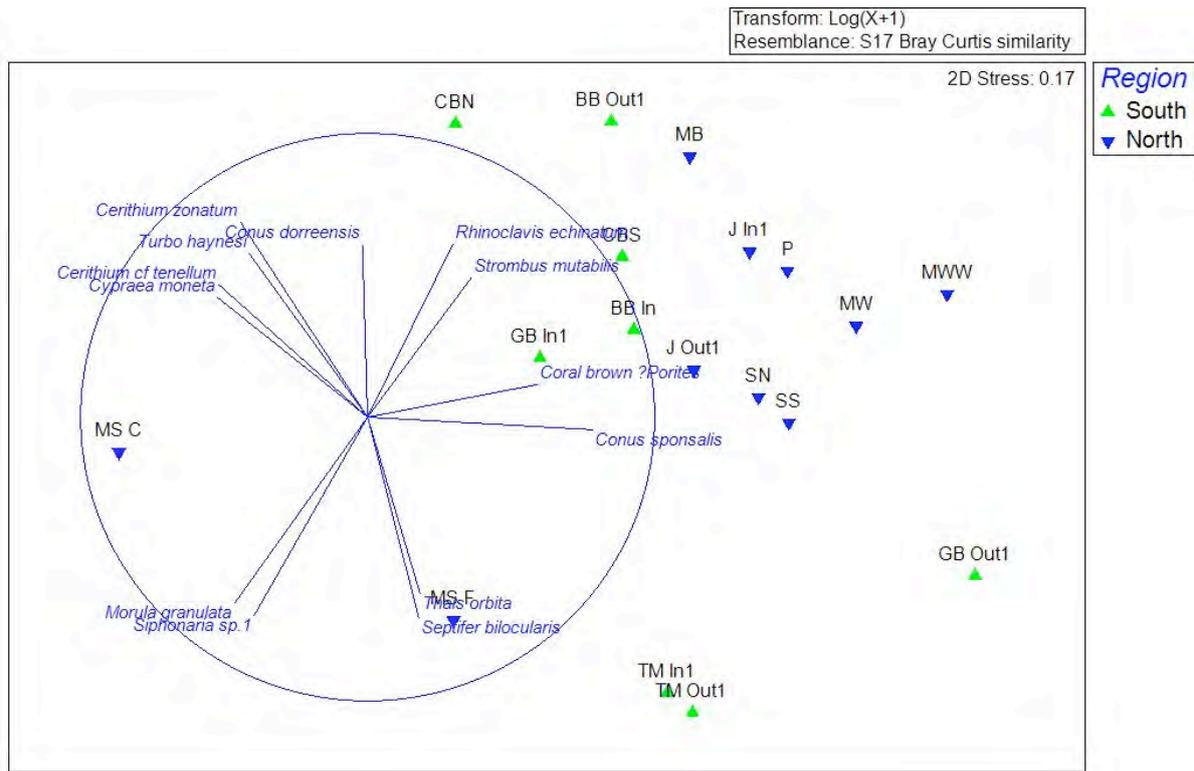


Figure 1. Nonmetric multidimensional scaling analysis of 10 sites in the North and 8 sites in the South sampled in 2007. Species shown in the biplot had $r \geq 0.60$.

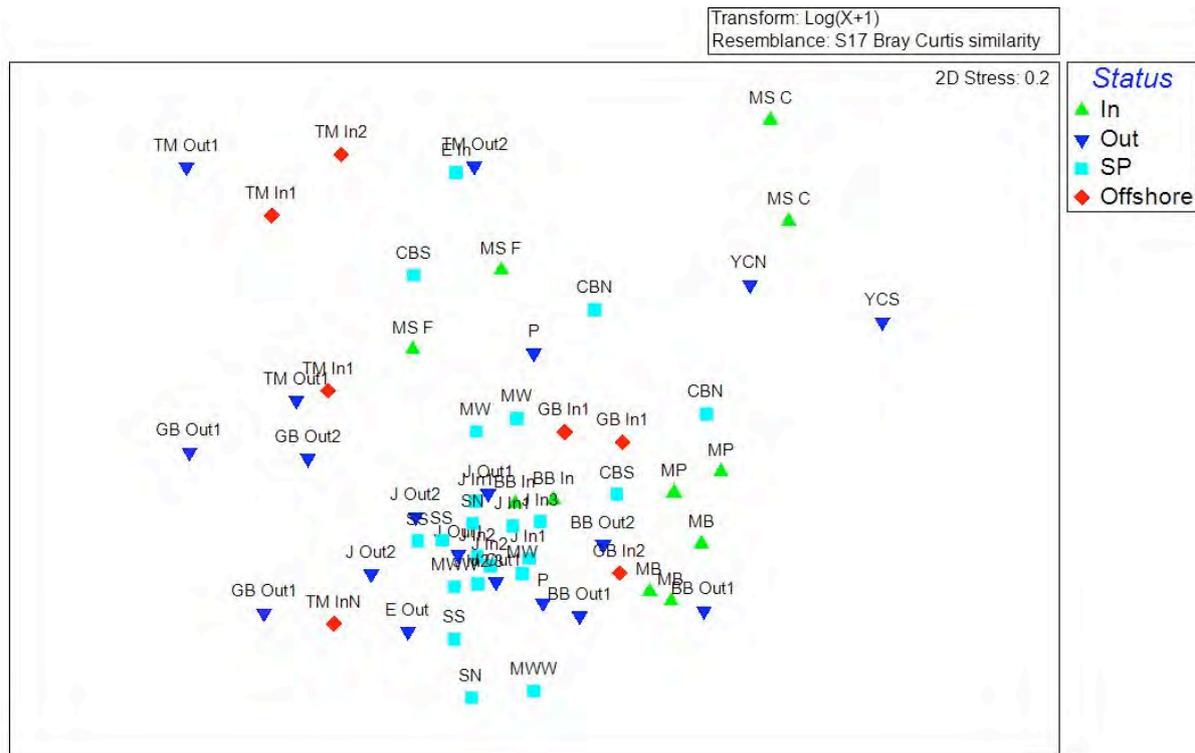


Figure 4. Nonmetric multidimensional scaling analysis of all sites at all times in 2007, 2008, and 2009 of sampling, identical to Figure 3, but points reversed left to right. In = in Sanctuary Zone, Out = outside Sanctuary Zone, SP = in Special Purpose Area in a Sanctuary Zone, Off shore = inshore of Sanctuary Zone that does not extend to the shore.

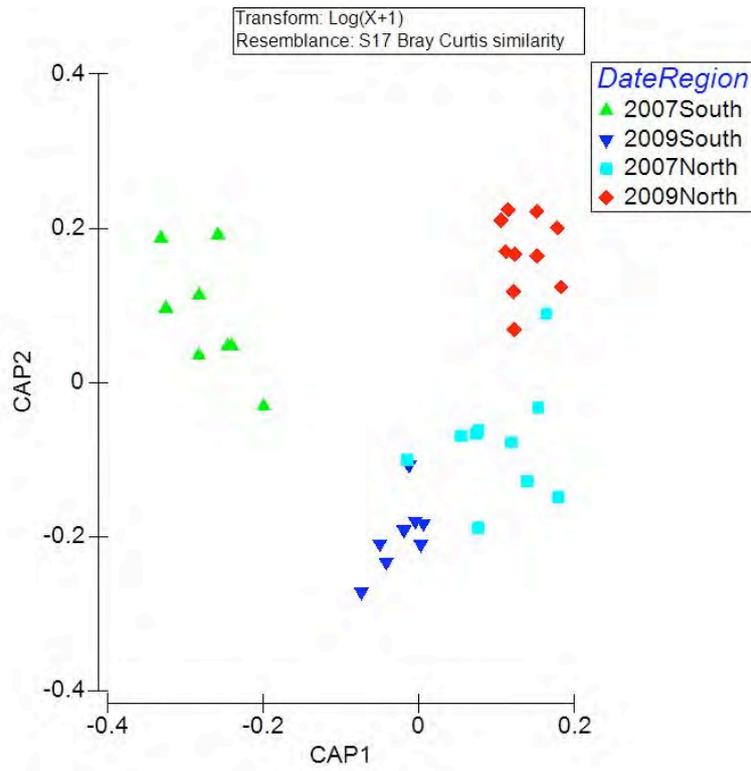


Figure 5. Canonical analysis of principal coordinates for the 18 sites sampled in 2007 and 2009. The analysis assumes that there are four groups made up of sites in the north or south of the Park in 2007 and 2009.

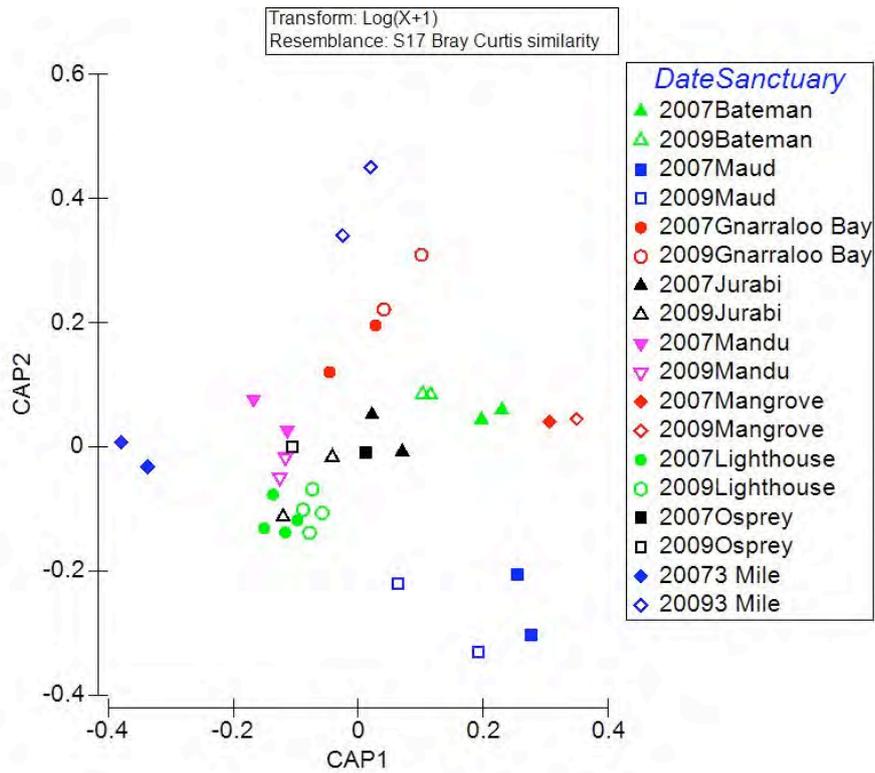


Figure 5. Canonical analysis of principal coordinates for the 18 sites sampled in 2007 and 2009. The analysis assumes that there are 18 groups made up of sites associated with nine sanctuary zones sampled in 2007 and 2009.

**Chapter 7: Do environmental variables explain differences in
macroinvertebrate assemblages between intertidal rocky
platforms?: a pilot study**



Photo by Robert Black

Jake Loughridge at Yardie Creek 1, which has a relatively rough surface.

Introduction

The macroinvertebrate fauna was so variable among sites that we wondered whether there were features of the platforms that might influence the assemblage of macroinvertebrates. Even though we had attempted to select sites that had basically similar platforms, we recognized that there were differences in the kind and amounts of algae and sediment, the occurrence of seagrass, bare rock, and rubble, and the numbers and size of depressions in the surface. We decided to quantify aspects of the nature of the platform surface to see whether these variables explained some of the variation in the assemblage.

Materials and Methods

Environmental features

In February 2009 we conducted pilot studies to investigate how we could characterize the platforms. This work was done as part of a Fourth-Year Research Project at the University of Western Australia by Jacob Loughridge. In 0.25 m² quadrats we recorded broad categories of algae (algal mat, foliose brown, foliose green, other), sediment (cobble, consolidated fine sediment, fine gravel, fine sand, fine silt), the presence (1) or absence (0) of seagrass, bare rock, and rubble, and the number of depressions that were < 5 cm deep, 5-10 cm deep and >10 cm deep. We used a light 200-cm chain and a heavier 740-cm chain and tape measures to calculate rugosity indices at two spatial scales. We measured the linear distance between the ends of the chain after it had been placed on the surface of the platform so that it followed the contour of the surface. The index was the arcsine of the square root of the proportion that the measured distance made of the length of the chain expressed as degrees, so its maximum would be 90 if the surface were absolutely flat, and less than that when the surface was rough.

In July 2009, we completed our standard sampling of the macroinvertebrates at 15 sites in the northern part of Ningaloo Marine Park, as described in Chapter 1.

Statistical analyses

We calculated the average values from 10 replicate 0.25 m² quadrats from each site for the two categorical variables and eight continuous environmental variables. We used the packages *vegan* (Oksanen et al. 2010) and *cluster* (Maechler et al. 2005) of the statistical program R (R Development Core Team 2009) to calculate dissimilarity indices (distance matrix) for the data in Table 1 (function “*gower*” in package “*cluster*”) and for the data from the macroinvertebrates, after a Hellinger standardization (function “*decostand*” in package “*vegan*” then function “*dist*” with method “*eucl*” in package “*vegan*”). We used function “*cmdscale*” which performs classical (metric) multidimensional scaling, also known as principal coordinates analysis, to represent these multivariate data sets about the 15 sites in a two-dimensional ordination. As a direct comparison of the two distance matrices, we used the function “*mantel*” in package “*vegan*”. We also used package “*rdaTest*” (Legendre and Durand 2010) to perform canonical redundancy analysis, and plot the results to illustrate how the physical variables were related to the ordination of the sites according to the macroinvertebrate assemblages.

Results

Table 1 shows the table of means of the environmental variables measured at 15 sites in the northern Ningaloo Marine Park. The Rugosity measure with the 200-cm chain was negatively correlated with the numbers of depressions that were 5-10 cm deep and > 10 cm deep because the high values of Rugosity.200cm indicate a smooth surface. Rubble was positively correlated with depressions < 5 cm deep and bare rock.

In a multivariate view of the physical variables, Figure 1 shows the ordination of the Gower dissimilarity indices for the ten physical variables, and Figure 2 shows the same kind of ordination for the euclidean distances of the macroinvertebrate assemblages after a Hellinger standardization of the same 15 sites. The mantel statistic, which is the parametric Pearson product-moment correlation coefficient between the values in the two dissimilarity half

matrices (the set distances between all pairs of the 15 sites) is 0.79364, with $p = 0.001$ from 999 permutations of the data. Thus, the dissimilarities between pairs of sites for the physical data and for the macroinvertebrate assemblages were highly similar.

A second multivariate analysis that combines two dissimilarity matrices is Canonical Redundancy Analysis (RDA) (-using package “rdaTest” and function “rda” in package “vegan”). Figure 3 shows the ordinations of the macroinvertebrate assemblages without and with the constraint of the information about the environment. The two top panels show that the relative positions of some of the sites alters when the constraint is applied, and the clustered sites in the left middle of the top panel are spread apart in the second panel. Both the axes in the plot contribute significantly to the pattern shown. The third panel in Figure 3, a mirror-image repeat of the second panel, shows more clearly the correlation of the physical variables with the two axes. Large values of Rugosity.740 indicate smooth surfaces over 7.4 meters; this variable is correlated with the vertical axis in the ordination, which contrasts the sites with smooth surfaces at this spatial scale (Pilgramunna and Mandu Cobble) with the sites that have rough surfaces (Mangrove Bay and Point). The Rugosity.-200 cm variable and the variables about numbers of depressions are negatively correlated, and these variables are correlated with the differences in the assemblages at the smooth Jurabi sites and pitted surfaces of the Yardie Creek sites.

Discussion

This pilot study about the influence of the physical features of the platforms on the assemblages of macroinvertebrates suggested that the effect could be great. The Mantel test showed a remarkable similarity in how much members of a pair of sites differed in their assemblages and in their environmental features. This similarity is reflected in the similar spatial pattern of the sites in the two ordinations in Figures 1 and 2. Yardie Creek 1 and 2, Mangrove Bay and Point and Mandu Cobble are separated from the other sites in both figures, and the northernmost sites cluster together in the middle left of each figure.

Figure 3, with information about the environment, changes the ordination of the sites according to their macroinvertebrate assemblages, suggests that the two rugosity indices play contrasting roles (because their correlations with the axes are at an angle), and that the rugosity index from the 200-cm chain and the counts of numbers of depressions are measuring the same feature (because their correlations with the two axes are about 180 degrees apart).

We used the insights from this pilot study to refine what we measured about the environment in a more detailed study described in Chapter 8.

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Acknowledgements

We thank Todd Bond for discussions about geomorphology and the measures of the environment used in this study.

Tables

Table 1. Average of 10 replicate measures of features of the substratum at 15 sites in February 2009.

Codes for Foliose Algae are: B brown; BG brown and green; Bgm ?; G green; O other.

Codes for Sand are: CFS consolidated fine sediment; COB cobble; FG fine gravel; FS fine sand; FT fine silt.

Site	Categories		Presence or absence			Number			Rugosity index	
	Foliose Algae	Sedi-ment	Sea-grass	Bare rock	Rubble	D<5	D5-10	D>10	200cm	740cm
Jurabi In 1	BG	FS	0.00	0.00	0.50	2.90	1.30	0.20	82.50	79.80
Jurabi In 2	BG	FS	0.30	0.10	0.20	1.30	1.50	0.50	82.15	80.87
Jurabi Out 1	BG	FS	0.00	0.00	1.00	3.70	0.90	0.60	80.69	81.30
Jurabi Out 2	BG	FS	0.00	0.00	0.30	3.20	1.60	0.20	81.94	82.51
Mandu Cobble	O	COB	0.00	1.00	1.00	3.40	1.90	0.90	76.88	82.44
Mandu Flat	G	CFS	0.00	0.10	0.70	4.00	1.80	1.30	81.67	83.56
Mangrove Bay	BG	FT	0.00	0.00	0.40	2.90	2.00	1.10	70.87	78.93
Mangrove Point	BG	FG	0.00	0.00	0.33	2.11	1.00	0.78	74.50	81.72
Mildura Wreck	BG	FS	0.30	0.10	0.40	2.30	0.60	0.20	81.23	83.31
Mildura Wreck West	BG	FS	0.50	0.00	0.90	3.50	0.50	0.10	83.15	77.80
Pilgramunna	BG	CFS	0.00	0.00	0.40	4.60	0.00	0.00	86.36	86.19
Surfers North	BG	FS	0.50	0.00	0.80	4.00	0.50	0.60	78.65	81.09
Surfers South	BG	FS	0.80	0.00	0.80	2.80	0.70	0.30	81.18	82.66
Yardie Creek 1	B	CFS	0.00	0.90	1.00	5.40	1.10	1.40	76.17	81.81
Yardie Creek 2	Bgm	CFS	0.00	0.60	0.90	4.20	2.10	1.00	73.51	79.38

Figures

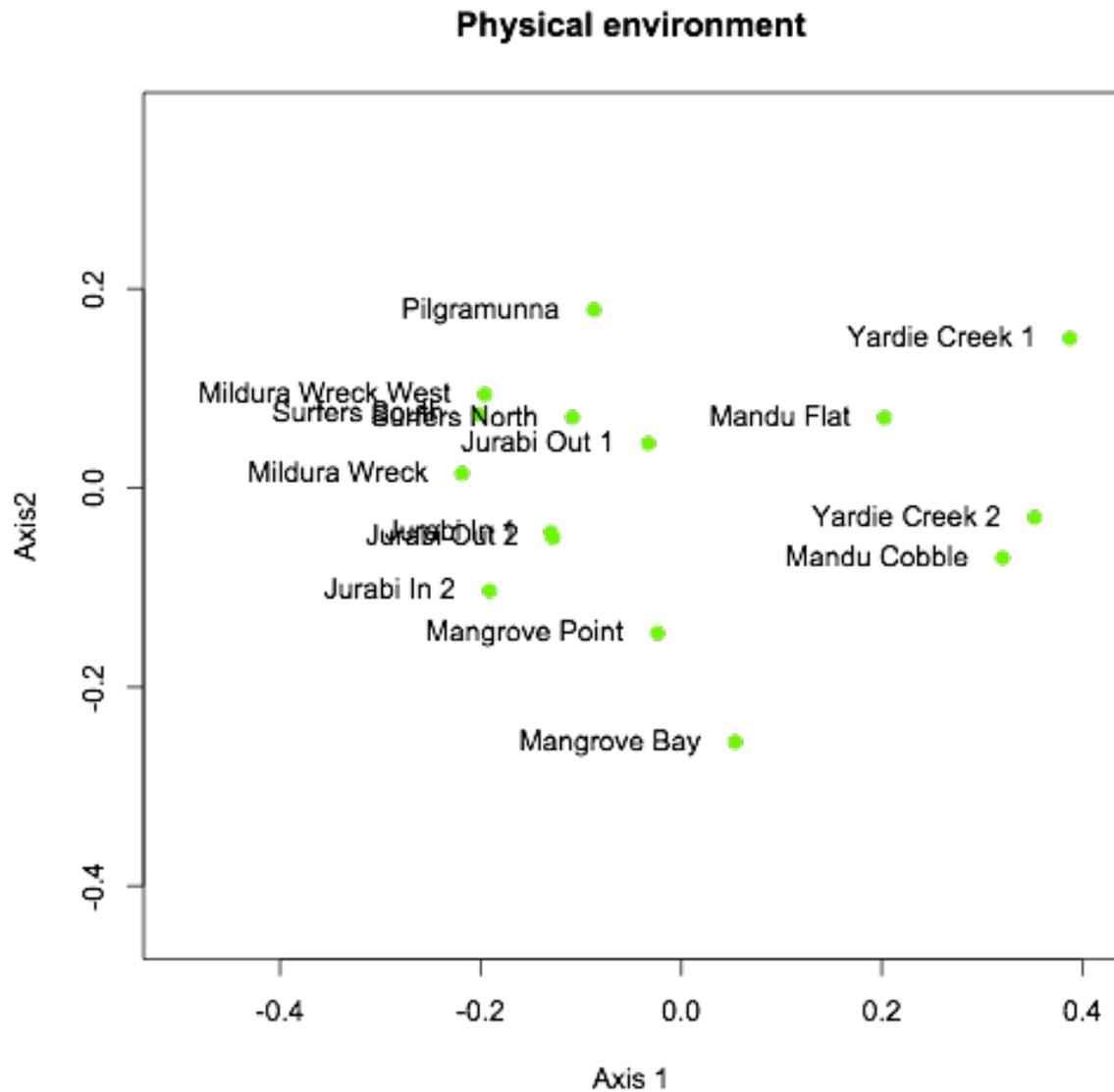


Figure 1. Principal coordinates analysis of the dissimilarity matrix using the “Gower” index for the physical variables (Table 1) for 15 sites in the north of Ningaloo Marine Park in February 2009.

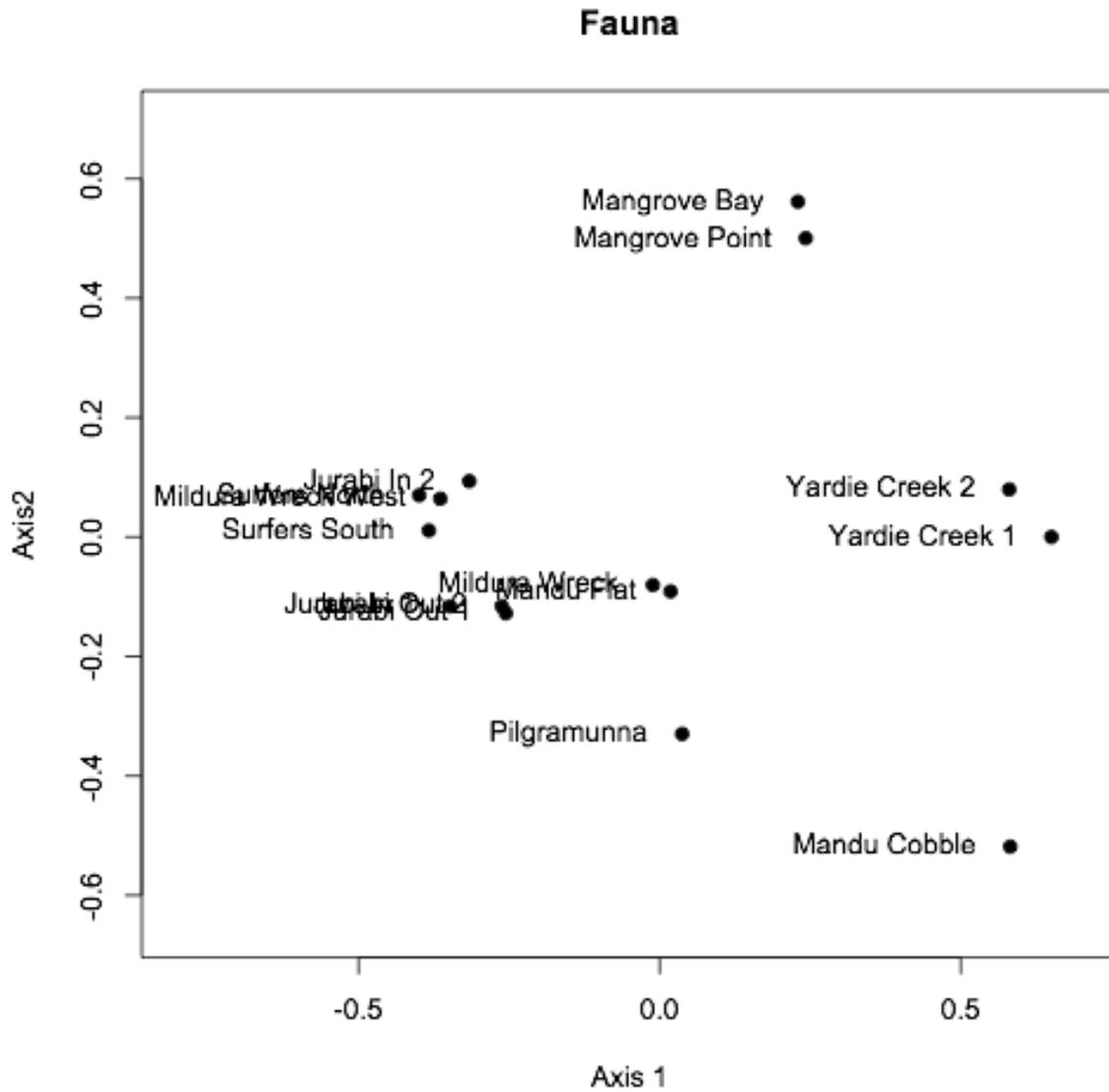


Figure 2. Principal coordinates analysis of the euclidean distance dissimilarity matrix for the macroinvertebrate assemblages at 15 sites in the north of Ningaloo Marine Park in July 2009.

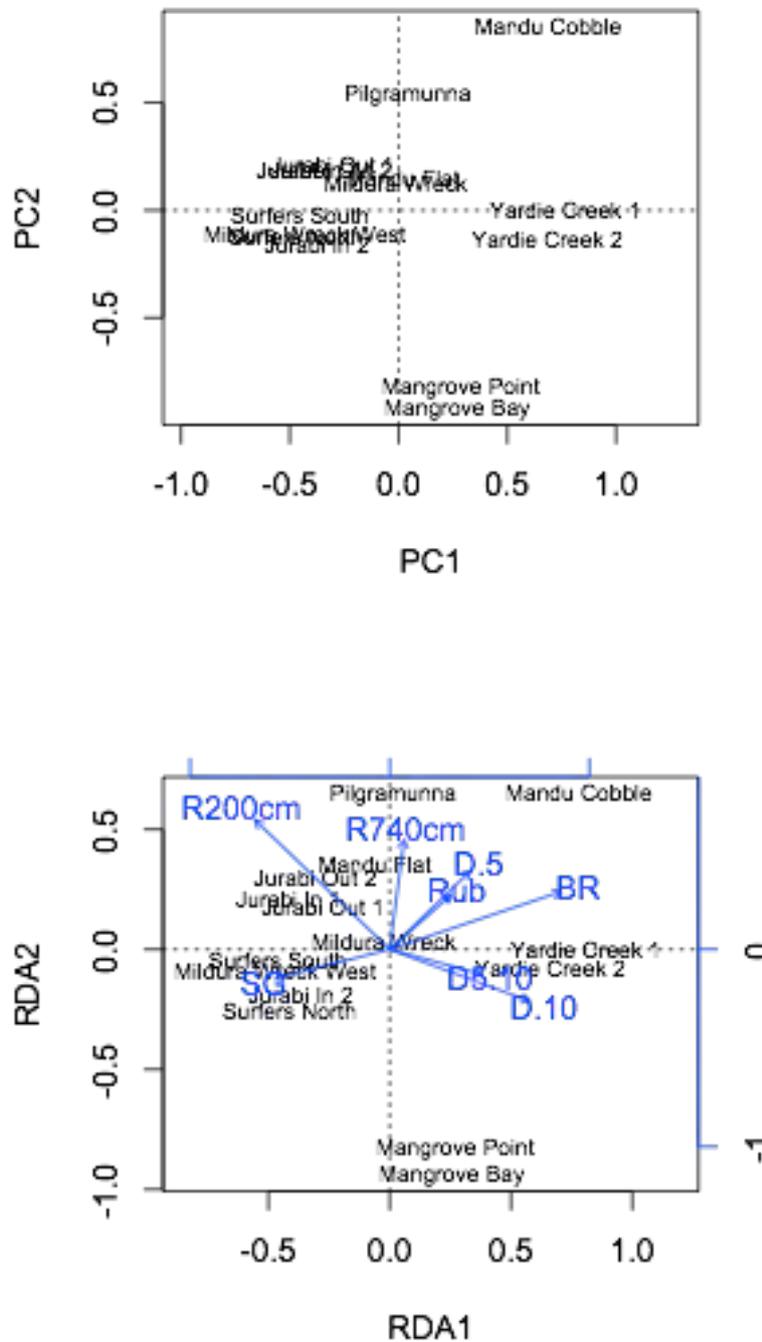


Figure 3. Principle coordinates analysis of the euclidean dissimilarity matrix of Hellinger transformed macroinvertebrate assemblages without (top) and with (bottom) the constraint of the eight continuous variables from the physical data set (Table 1). The blue arrows represent the correlations of the physical variables with the RDA axes. The lower figure is repeated on the next page in a larger format, and as a mirror image.

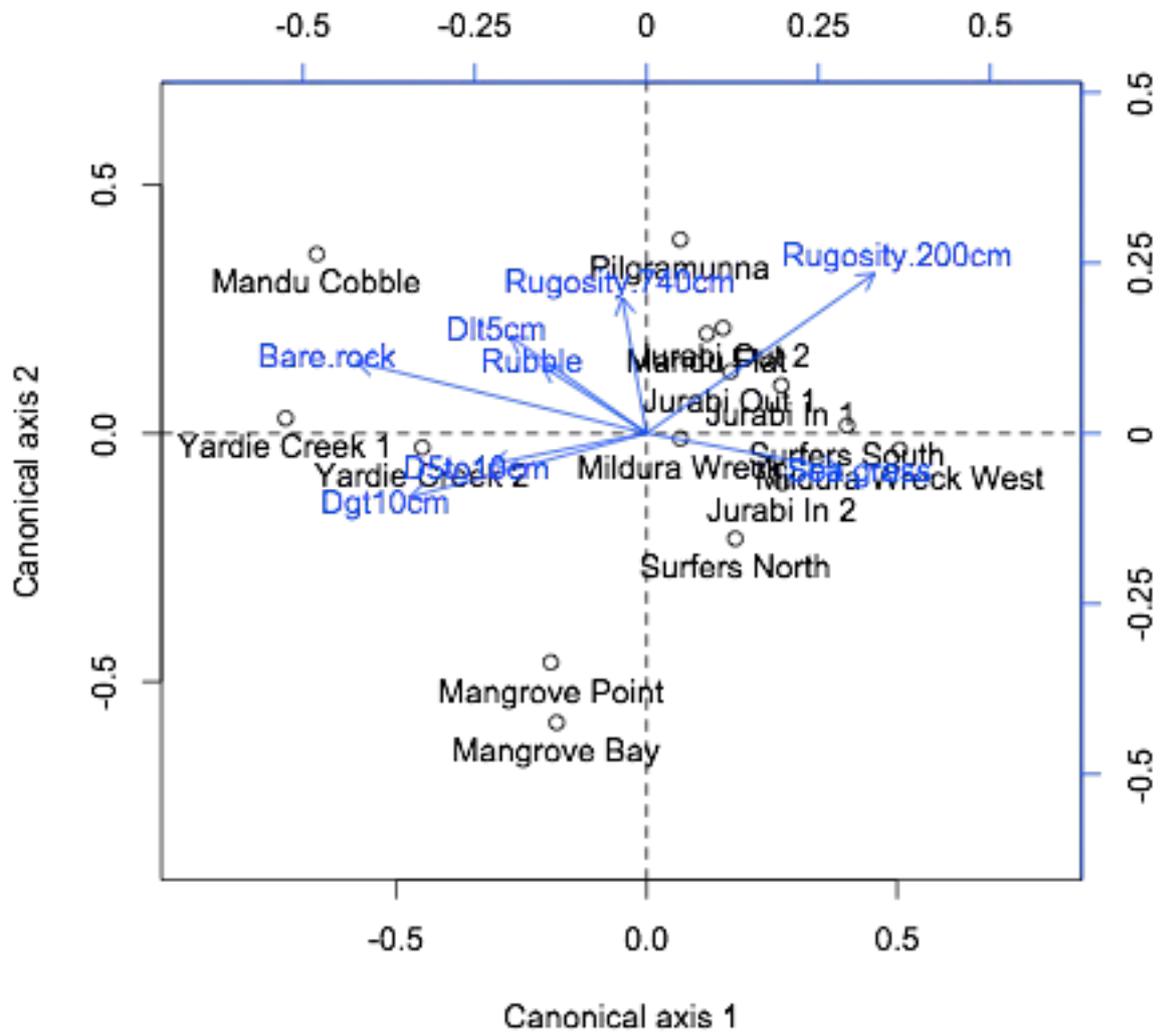


Figure 3 concluded. Rugosity.740cm and Rugosity.200cm increase in value as the surface is smoother, and so the arrows indicating their correlation with the two axes point toward the sites with smoother surfaces. The variables associated with the number of depressions in a 0.25-m² quadrat (Dlt5, D5to10, Dgt10) are almost 180 degrees in opposition to Rugosity.200cm. Sea grass occurred at Surfers South. Mangrove Bay and Mangrove Point were undulating over 740 cm.

Chapter 8: Linkages between intertidal invertebrate assemblages and shore platform morphology in the Ningaloo Marine Park, Western Australia.

This chapter is the thesis submitted as part of an Honours Degree in Marine Science by

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Todd Bond, September 2009- photo by R. Black



THE UNIVERSITY OF
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Linkages between intertidal invertebrate
assemblages and shore platform morphology
in the Ningaloo Marine Park, Western
Australia.

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Abstract

The analysis of spatial patterns is important for scientists specialising in both geomorphology and ecology for understanding variance at different scales. Identifying common processes controlling the morphology of rock platforms and intertidal invertebrate assemblages provides an understanding of the “bigger picture” and an insight into landscape ecology. The aim of this project was to develop a typology of shore platforms within the Ningaloo Marine Park, Western Australia from the investigation of morphological features measured onsite during visits and offsite using charts and maps to determine if shore platform morphology can help explain and predict an intertidal invertebrate assemblage. Cluster analyses were used to investigate patterns of morphological similarity in all morphological data and subsets of data to determine the best description of site morphology. The subset of data used to determine morphotypes included 10 variables measured both onsite and offsite and identified 5 morphotypes. Site morphology differed regionally with the major differences likely due to wave energy and protection by offshore reef. The patterns of dissimilarity of the assemblages of macro-invertebrates at each site from counts in 20 1m² quadrats were correlated to the patterns of dissimilarity of morphological characters of the site. Furthermore, ordinations of the invertebrate assemblage at each site constrained by the factor morphotype show more defined groupings of sites with the same morphotype. Invertebrate assemblages differed regionally and may be explained by broader scale processes not considered in this project. Predicting the abundance of key animals’ (i.e. *Cypraea* spp., *Tridacna* spp., *Conus* spp. and Corals) is difficult using this typology but the abundance of other species (*Siphonaria* spp., *Thais orbita*, *Cronia avellana*, *Strombus mutabilis*, and *Septifer bilocularis*) can be predicted with confidence. This project will add base knowledge to rocky coast geomorphology in Western Australia and provide coastal managers at Ningaloo with a tool to guide and focus site-specific invertebrate research.

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07/06/2010

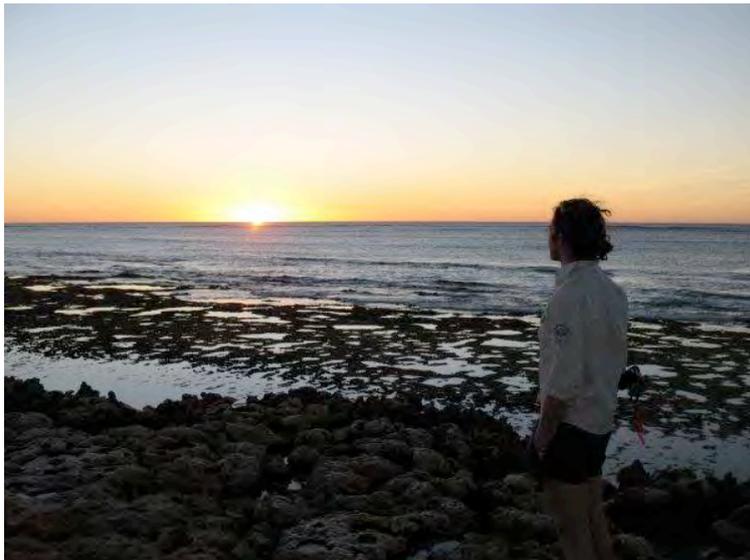


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1. Introduction

For scientists specialising in both geomorphology and ecology the analysis of spatial patterns is important to understand variance at different scales. With some exceptions, most ecologists focus their work at a fine scale over both short time periods and spatially small areas (Schoch & Dethier, 1996). However, generalisation requires the ‘bigger picture’ and considering the development of the geomorphic landscape through broad processes and morphological attributes, as opposed to a single, fine scale study site which may help to see this picture. The use of geomorphology as a predictive tool for communities and habitats is a multidisciplinary area that has not been fully implemented or utilised and is sometimes referred to as ecogeomorphology. Ecogeomorphology combines geography, geology, meteorology, ecology and biology and may not be as difficult to study as first thought. Although some community ecologists may believe that ‘scaling up’ to a landscape is difficult due to environmental variation or ‘noise’, predictions and extrapolation of data may be the only short term answer for areas either inaccessible or too large to completely sample (Schoch & Dethier, 1996).

Although many researchers incorporate knowledge from a number of disciplines to explain phenomena in their field of expertise, it is rare that research is developed around the concept of combining two disciplines. Schoch and Dethier (1996) conducted one such study, investigating statistical linkages between organism abundance and the geomorphology of the rocky shoreline in Washington, United States of America. Their outcomes showed that biota on coastlines with different geomorphology did significantly vary. More locally, investigations by Cassata and Collins (2008) concluded that the geomorphology of the subtidal Ningaloo Reef correlated with habitat distribution. In both instances, geomorphology could be used as a proxy for either organism abundance or habitat type and could be extrapolated over larger areas.

Protecting extensive stretches of coastline such as that in the Ningaloo Marine Park (herein after referred to as *NMP* or *Ningaloo*), highlights how important it is to understand broad-scale spatial patterns in intertidal ecology. Marine managers protecting these types of coastlines require cost and time effective methods to determine what species and habitats are where. It is therefore the aim of this project to investigate the broad scale patterns in platform morphology throughout the NMP and determine any relationships between shore platform morphology and intertidal macro-invertebrate assemblages. This aim will be fulfilled through four key objectives:

1. Determine the site-specific geomorphology and invertebrate assemblages on intertidal platforms for sites selected in the NMP;
 2. Determine broad scale geomorphology of selected sites from aerial imagery and marine charts;
 3. Classify sites into morphotypes and identify potential drivers determining their morphology;
- and

4. Determine if any relationships exist between platform morphology and invertebrate assemblages.

Significance

The Ningaloo Marine Park

The charm of Ningaloo Marine was once only known to a small number of Western Australians and an even smaller number of Australians camped along its coastline (Western Australian Planning Commission, 2003). Tourist numbers from intrastate, interstate and particularly overseas has significantly increased over the past ten years to over 200,000 per annum (Western Australian Planning Commission, 2003). Although most tourists from overseas bring and spend more money than inter- and intrastate tourists, their potential impact on the marine environment is concerning (Western Australian Planning Commission, 2003).

The state government gazetted the NMP as an A-Class Marine Park in 1987 and it is currently the responsibility of the Department of Environment and Conservation within State waters and the Commonwealth Department of Environment and Heritage in Commonwealth waters (CALM, 2003). The NMP encapsulates the Ningaloo Reef that stretches from the top of the Northwest Cape to Red Bluff (Figure 1), over 290 kilometers of coastline (CALM, 2003) and is the largest fringing reef in Australia (CALM, 2003, CALM, 2005, Collins et al., 2003). The vision for the NMP is to preserve or better the condition of *the marine flora and fauna, habitats, sediments and water quality* and is being managed with sanctuary zones, coupled with education, research, enforcement, monitoring and surveillance (CALM, 2003).

Sanctuary zones comprise over one third of the NMP, representing the major marine habitats, flora and fauna (CALM, 2005) (Figure 1). The success of sanctuary zones at Ningaloo should be determined to justify their retention or future expansion. To determine this it must first be known what is currently present (e.g. particular species), the quality of what is present (e.g. water quality or species diversity) and what is present after threats have been removed (e.g. through monitoring over time). The Western Australian Marine Science Institute (WAMSI) (Node 3.2.2b) is undertaking an inventory of invertebrates on intertidal platforms within the NMP and preliminary results show great spatial variability. One objective of this WAMSI project is to determine differences in invertebrate assemblages in and out of sanctuary zones but differences due to other factors must also be considered. The results of this project will begin to describe if platform morphology and broader physical variables help to explain the intertidal invertebrate assemblages and provide recommendations for future monitoring, research and application to coastal management.

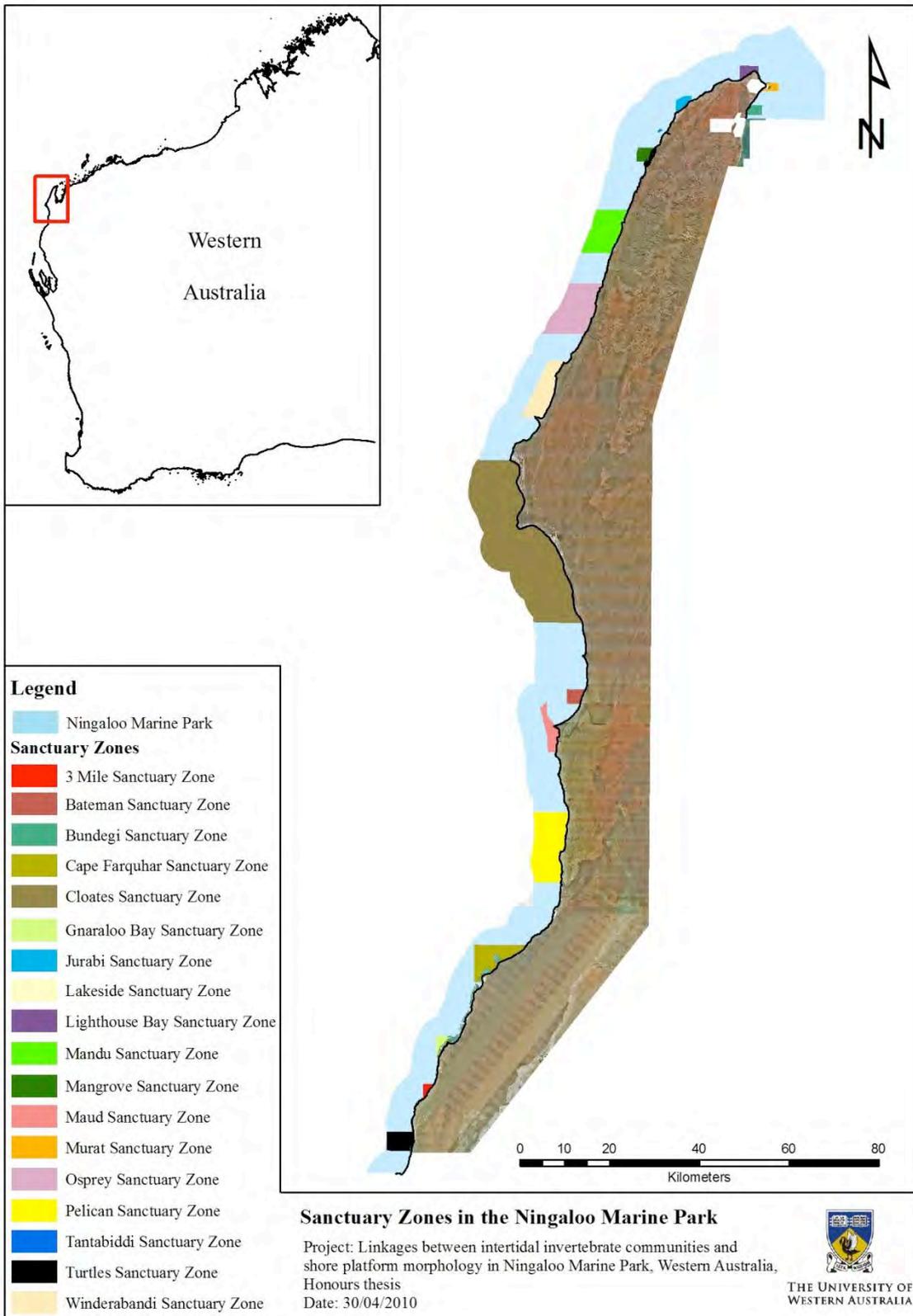


Figure 1: Sanctuary zones in the Ningaloo Marine Park. Sanctuary zone boundary sourced from the Department of Environment and Conservation.

State of Knowledge of Rocky Coasts

Approximately 51% of the Australian coast and 57% of the Western Australia coast is rocky (Short, 2010) but the extent of rocky coast geomorphology research in Australia and Western Australia is limited when compared with its sandy beach counterparts. A large majority of the research conducted on rocky coast geomorphology focuses on modeling rocky coasts with little addressing the entire morphology. Workers that have provided morphological descriptions of the Australian rocky coast (Hills, 1949; 1972; Jutson, 1940; 1948; 1949) have focussed their work on the east coast of Australia and these descriptions are not likely to apply in Western Australia. It is therefore hoped that this project will assist in adding base knowledge to rocky coast geomorphology in Western Australia, specifically Ningaloo.

Background

Regional Setting

The regional setting of Ningaloo is set by a series of anticlines that have resulted in the formation of the Cape Range (Wyrwoll, 1990). The Cape Range runs parallel to the coastline and the Ningaloo Reef with Tantabiddi Limestone the general geological setting onshore (Wyrwoll, 1990; Collins et al., 2003). The contemporary Ningaloo Reef has formed on top of an existing limestone reef platform, forming a broad reef flat of up to 100 metres wide and close to mean low water spring tide level (Sanderson, 2000). Landward the reef encloses a lagoon, generally no deeper than 5 metres (Sanderson, 2000). The coastal margin has a narrow Holocene beach-dune fringe that is unstable in some places and underlain by a Last Interglacial reef that crops out along the coast (Sanderson, 2000, Collins et al., 2003). Figure 2 is an idealised cross section of Ningaloo Reef structure and lithofacies units present.

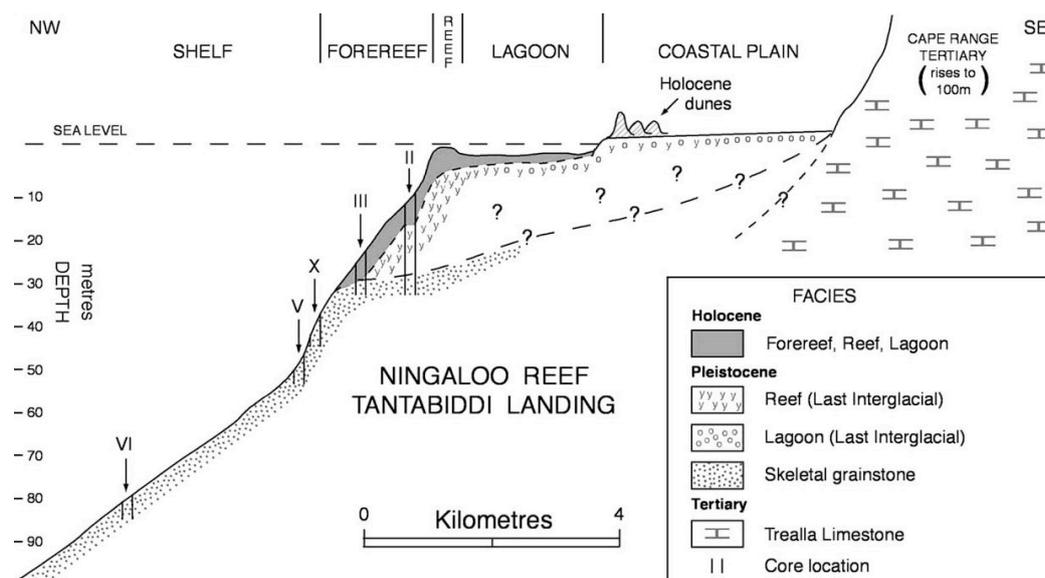


Figure 2: Idealised northwest-southeast cross section of the Ningaloo Reef and surrounds (Collins et al., 2003).

Meteorological Conditions

The Ningaloo coast sits at the northern extent of anticyclones in summer and within their path in winter, resulting in calm conditions in summer and strong east and south westerly winds in winter and spring (Sanderson, 2000) (Table 1). The region experiences strong sea breezes that commonly exceed 30km/hr in late winter, spring and early summer which in turn results in an increased number of short period waves (Sanderson, 2000). A more detailed description of the wind regime at Ningaloo will be presented as result of this project.

Table 1: Percentage frequency of onshore winds for Ningaloo. Data are taken the Bureau of Meteorology as cited in Sanderson (2000). Data is from Carnarvon over a 48 year period.

Season	% of S to SW winds	% of N to W winds	% of S to SW winds >30 km/hr	% N to W winds >30 km/hr
Summer	84	13	37	1
Autumn	78	14	15	1
Winter	60	23	8	2
Spring	84	14	35	2

Silvester and Mitchell (1977) described the wave climate at Ningaloo to be dominated by consistent swell waves from the southwest in winter with heights of 2-3 metres and from the south in summer with heights of 1-2 metres. The presence of the outer reef significantly reduces the impact of swell waves on the coastline, with an estimated 70-90% of swell wave energy attenuation (Sanderson, 2000). Strong sea breeze winds generate short, steep sea waves within the fetch-limited lagoon that frequently have heights of 1-2 metres and periods of 4-6 seconds (Sanderson, 2000). Extreme waves as a result of storms and cyclones are expected to impact the coast on a yearly basis resulting in inundation and erosion of the nearshore.

The tidal range at Ningaloo is semi-diurnal and spring tides reach 1.8m (Table 2). Residual water level is not recorded throughout Ningaloo but thought to differ as a result of mean sea level pressure and setup. Exmouth and the Ningaloo coast experienced a surge of several meters during tropical cyclone Vance (BoM, 2000). Additionally, water levels at the intertidal are likely to be affected by infragravity¹ waves (pers. comm. R. Lowe, October 2009).

Table 2: Tidal ranges for the Ningaloo coast (Department of Defence, 2009).

	HAT*	MHHW*	MLHW*	MSL*	MHLW*	MLLW*	LAT*
Tidal Height (m)	2.8	2.3	1.7	1.4	1.1	0.5	0.0

* HAT= Highest Astronomical Tide; MHHW= Mean High High Water, MLHW= Mean Low High Water; MSL= Mean Sea Level, MHLW= Mean High Low Water; MLLW= Mean Low Low Water; LAT= Lowest Astronomical Tide.

Occasional tropical cyclones bring gale force winds to the area and between the period of 1907 to 1993, 79 tropical cyclones passed the 5° latitude/longitude grid including Exmouth at 110-115° east and

¹ Infragravity waves have periods above about 30 seconds and are generated by wave groups breaking in the surf zone.

20-25° south (Sanderson, 2000). Associated wind conditions on these cyclones will be discussed as a result of this project.

2. Research methodology

Approach

The research approach of this project is similar to that by Schoch and Dethier (1996) and Travers (2006), whereby a number of physical variables were investigated and clustered together to determine like sites. The key physical variables determining clusters were then summarised to describe each resulting morphotype. The second aspect of the approach was to determine whether each morphotype was characterised by different assemblages of macro-invertebrates.

Physical variables were measured at two different scales - fine scale from site visits and broad scale from aerial photography and charts - to investigate if one scale of data can be used without the other. In addition, subsets of the data were investigated to gain an understanding of which variables most clearly delineated the morphotypes.

Design

The project has 32 sites (Table 3) within the study area from Mildura at the northern tip of North West Cape, to 3 Mile Camp on Gnarlouo Station in the south (Figure 3). All sites are located within the NMP and distributed across 2 degrees of latitude and approximately 270 kilometres of coastline. Sites were chosen to overlap with existing locations of sampling conducted by Professor Mike Johnson, Associate Professor Robert Black, Dr. Jane Prince and Dr. Anne Brearley for the WAMSI Node 3.2.2b. Sites were selected to be in and out of sanctuary zones, drained of water at low spring tide, have adequate platform width and length to incorporate a 15 metre crossshore by 50 metre alongshore sampling area towards the centre of a platform away from seaward and shoreward edges and on a relatively flat platform not dissected by channels or extensive and deep rock pools.

Sites have been sampled both in and out of sanctuary zones and are titled accordingly. For example the site *3 Mile In 3* (3MI3) is located at 3 Mile Camp, within the sanctuary and is the third site that has been sampled within the sanctuary. A site is different from a platform which is the entire stretch of continuous elevated intertidal rock surface. A platform can have more than one site and a number of different physical conditions on it as well as offshore and onshore.

Table 3: Sites previously sampled by WAMSI.

Section	Sites	Latitude S	Longitude E
North	Mildura Wreck (MW)	21°47'06.30"	114°09'54.52"
	Mildura Wreck West (MWW)	21°47'09.05"	114°09'44.85"
	Surfers North (SN)	21°47'13.05"	114°09'35.84"
	Surfers South (SS)	21°47'26.16"	114°09'14.37"
	Jurabi Out 2 (JO2)	21°50'44.64"	114°02'10.14"
	Jurabi Out 1 (JO1)	21°50'51.78"	114°01'51.30"
	Jurabi In 1 (JI1)	21°50'57.63"	114°01'33.43"
	Jurabi In 2 (JI2)	21°51'01.25"	114°01'26.81"
	Jurabi In 3 (JI3)	21°51'06.13"	114°01'21.89"
	Mangrove Bay (MB)	21°57'40.88"	113°56'25.43"
	Mangrove Point (MP)	21°57'50.14"	113°56'24.78"
	Mandu Cobble (MC)	22°08'43.16"	113°52'12.04"
	Mandu Flat (MF)	22°08'45.01"	113°52'11.25"
	Pilgramunna (PIL)	22°11'39.48"	113°51'17.38"
	Yardie Creek North (YCN)	22°19'36.17"	113°48'31.95"
	Yardie Creek South (YCS)	22°19'42.12"	113°48'29.52"
South	Bateman Bay Out 2 (BBO2)	23°02'17.90"	113°49'42.98"
	Bateman Bay Out 1 (BBO1)	23°02'37.76"	113°49'39.20"
	Bateman Bay In (BBI)	23°02'58.41"	113°49'24.34"
	Coral Bay South (CBS)	23° 9'24.01"	113°45'59.89"
	Coral Bay North (CBN)	23° 9'11.32"	113°46'06.00"
	Elles In (EI)	23°26'00.79"	113°46'52.76"
	Elles South (EO)	23°26'16.14"	113°46'48.08"
	Gnaraloo Bay Out 2 (GBO2)	23°45'36.72"	113°33'43.14"
	Gnaraloo Bay Out 1 (GBO1)	23°45'47.82"	113°33'30.24"
	Gnaraloo Bay In 2 (GBI2)	23°46'13.93"	113°32'15.93"
	Gnaraloo Bay In 1 (GBI1)	23°46'19.75"	113°32'10.30"
	Three Mile 3 (3MI3)	23°52'13.51"	113°29'48.00"
	Three Mile In 2 (3MI2)	23°52'30.39"	113°29'40.80"
	Three Mile In 1 (3MI1)	23°52'32.00"	113°29'38.68"
	Three Mile Out 1 (3MO2)	23°52'33.00"	113°29'37.63"
	Three Mile Out 2 (3MO1)	23°52'45.54"	113°29'25.42"

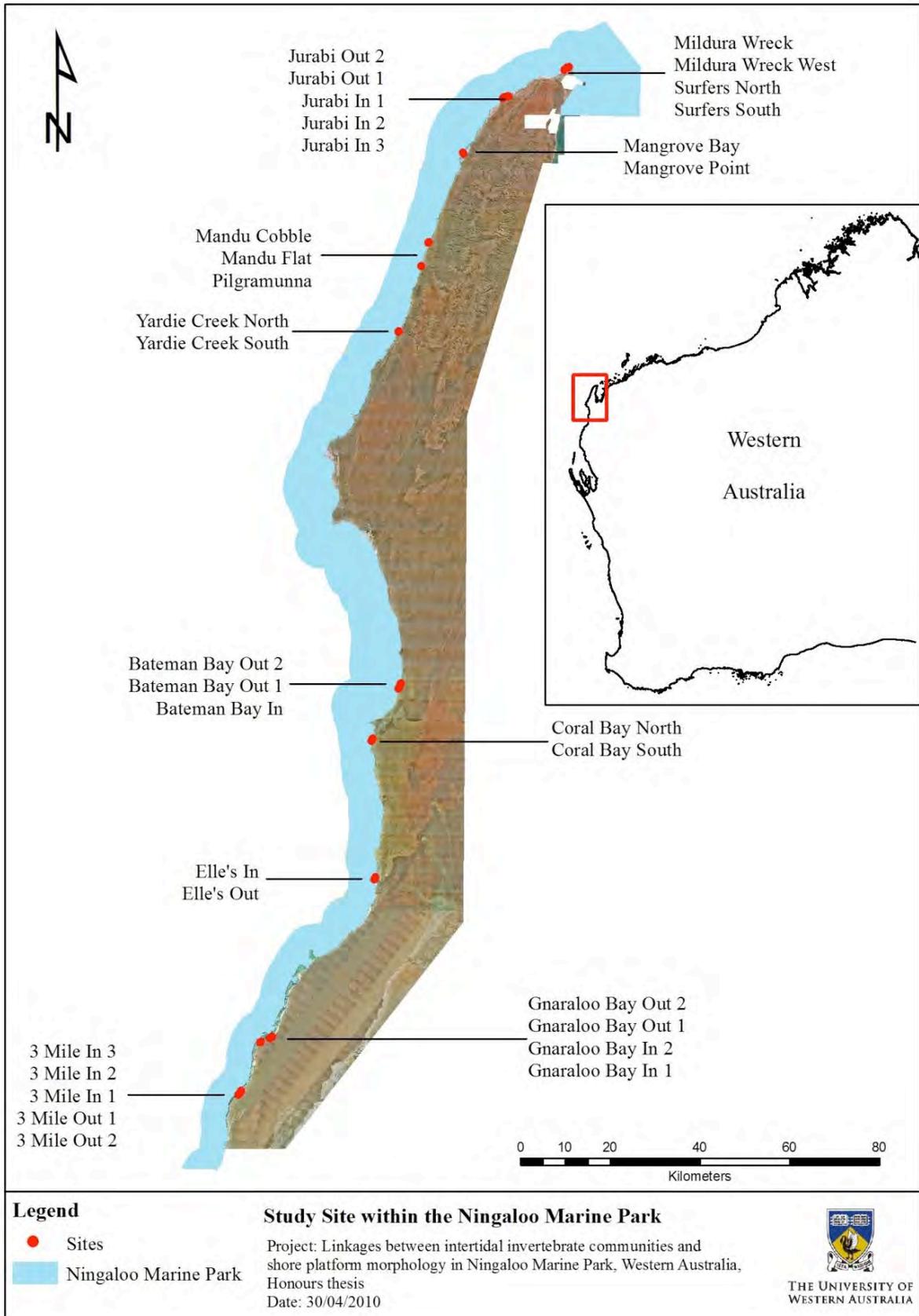


Figure 3: Study area with sites listed from north to south.

3. Platform Morphology

Introduction

Shore platform (herein after referred to as *platform*) morphology is shaped by the balance of geological conditions and forcings such as waves, tides and chemical weathering (Trenhaile, 1987; Sunamura, 1992; 2002, Kennedy, 2009). Rocky coasts research including platform morphology has been summarised by Trenhaile (1987) and Sunamura (1992). Sunamura (1992) classified current rocky coast development into three morphotypes (Figure 4): gently sloping platforms without a significant topographic break extending from the base of a cliff to the nearshore sea floor below low tide (Type-A); nearly horizontal platforms with a marked drop at their seaward edge (Type-B); and steeply descending cliffs that pass far below sea level (plunging cliffs). The development of these morphotypes was dependent on the recession of the coastal cliffs from the erosive force of waves and the resistance of the rock (Sunamura, 1992).

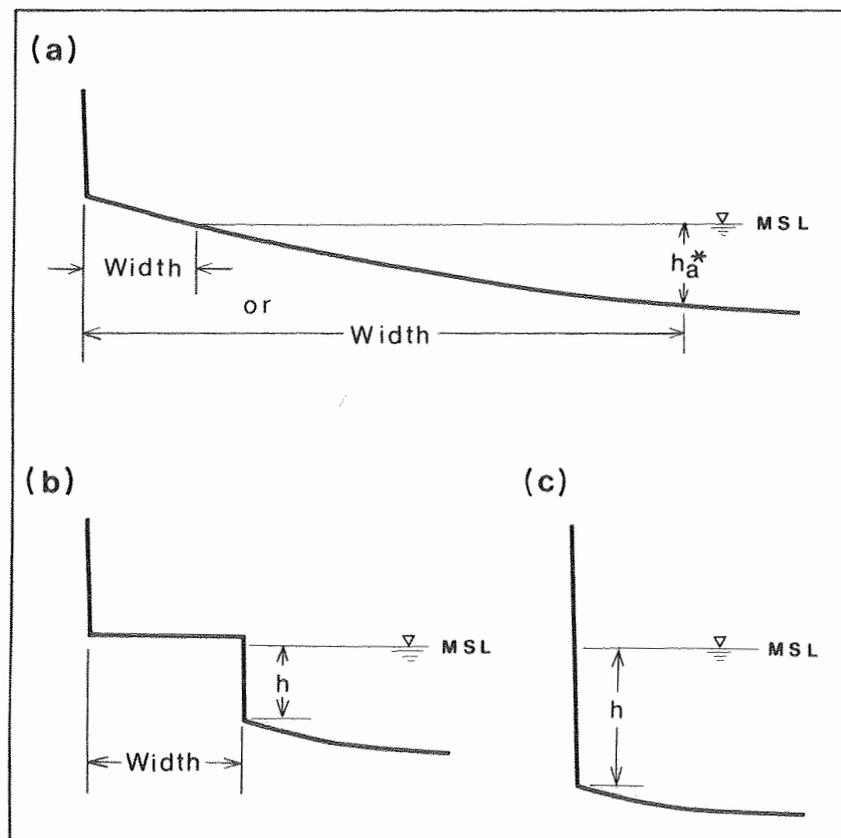


Figure 4: Schematic cross-section of three major morphologies of rocky coasts; (a) Type-A shore platform; (b) Type-B platform; (c) plunging cliff (Sunamura, 1992).

Nationally, work by Jutson (1948, 1949) and Hills (1949, 1972) described similar morphological features to Sunamura (1992) including low tide cliffs and nearly horizontal or sloping platforms with and without ramps. Regionally, Semeniuk & Johnson (1985) recognised four different types of rocky shore but only one had a platform. More recently, local work by Green (2008) investigated the rocky

embayed coast of the north metropolitan area of Perth, Western Australia and described four beach types, two included sandy beach with platform and pavement. Due to this gap in literature on the morphology of the rocky coast and shore platforms of Western Australia, the following discussion will explore the current knowledge of key attributes of rocky coasts globally with emphasis on platforms.

Platform Height, Width and Gradient

Platform height, width and gradient are the most important aspects of platform morphology (Trenhaile, 1978; 1987; Sunamura, 1991; 1992; Trenhaile et al., 1999). Literature outlining the determinants of height, width and gradient are summarised in Table 4 and described in detail in Appendix 1 – Extended literature review of platform height, gradient and width.

Table 4: Summary of literature on platform height, gradient and width.

Platform variable	Factors affecting variable	Affect
Height	<ul style="list-style-type: none"> • Intensity of waves (Kirk, 1977) • Strength of the platform forming rock (Gill, 1972) • Weathering of rocks (Hills, 1972; Bartrum, 1916) • Tidal range (Hills, 1972; Trenhaile, 1978) • Erosional history (Gill, 1972) 	<ul style="list-style-type: none"> • Increased height with increased rock strength (Trenhaile, 1987; Sunamura, 1991; Thornton & Stephenson, 2006) • Platforms cut by breaking waves are higher than those cut by already broken waves (Homma & Horikawa, 1965; Sunamura, 1973; 1975) • Conversely, no relationship between rock strength and height (Kennedy, 2009)
Gradient	<ul style="list-style-type: none"> • Distribution of wave energy across the profile of the platform controlled largely by tides (Trenhaile, 1983, 1987, 1997, 2002) • Ramps associated with wave energy (Hills, 1949; 1971; Healy, 1968; Trenhaile & Layzel, 1981) • Inheritance (Trenhaile, 2002) 	<ul style="list-style-type: none"> • Low gradients associated with high spring tidal height (Trenhaile, 1983, 2002) • Ramps occur in swell dominated coasts with a low tidal range ((Hills, 1949; 1971; Healy, 1968; Trenhaile & Layzel, 1981)
Width	<ul style="list-style-type: none"> • Wave energy (Kennedy, 2009) • Tidal controlled weathering (Trenhaile, 2002) 	<ul style="list-style-type: none"> • Wider platforms with higher wave energy (Kennedy, 2009) • Wide platforms at height of MSL and narrow platforms above and below MSL (Trenhaile, 2002)

In addition to these three major determinants of platform morphology it is predicted that other aspects of coastal geomorphology are likely to have an impact on platform morphology at Ningaloo, including the extent of fringing reef, the type of platform edge, the sediment on the platform surface and the morphology of the high water interface. These features are described in detail below.

Fringing Coral Reef

Ningaloo Reef is the longest fringing reef system in Australia and stretches the length of the study site, following the general shape of the coastline. Reef passes or gaps in the outer reef are a common feature and are responsible for nutrient and water exchange and the energy gradient through the

lagoon (Cassata and Collins, 2008). Sanderson (2000) described the relationship between the extent of the fringing coral reef with lagoon processes at two sites at Ningaloo and compared these with a similar temperate reef at Jurien Bay, Western Australia. Sanderson (2000) concluded that current velocities (both surface current and maximum residual current velocities) increased as the extent of offshore reef increased, while the significant wave height decreased. Additionally, the distance the reef is from shore can vary, determining the fetch of a site and the subsequent wave energy onshore. Sanderson's (2000) results suggested that a wide lagoon resulted in increased wave height and decreased current velocities.

Preliminary studies by Lowe *et al.* (Unpublished) have provided details to the extent of wave setup on the reef crest at Sandy Bay, Ningaloo and formed estimations as to the setup within the lagoon. As a function of offshore wave height, the wave setup on the reef obtained a maximum height of 0.5 metres when the offshore significant wave height reached 2 metres. Within the lagoon wave setup typically ranged between 60-80% of observed maximum reef values. Therefore, when investigating the impact of water level on shore platforms the presence and extent of offshore reef should be considered in addition to tidally induced changes in water level.

Platform Edge

A defining attribute of all rocky coasts is the terminus of a platform at low tide (see Figure 4). The presence of either Type A or B is dependent on the erosion history of the platform and inheritance from past sea stands (see Sunamura, 1992; Griggs & Trenhaile, 1994; Trenhaile, 2000). In addition, preliminary studies by Da Silva (2010) suggest that the presence of a low tide cliff reduces the amount of wave forcing exerted on the platform surface during times of lowered water level when compared against grading platforms of similar height.

Sediment

"Sediment" in its broadest sense includes all biogenic and lithogenic material, ranging from cobble-sized grains to sand and fine silt. Sediment can be sourced from three origins : (1) offshore supply, reworked lithogenic material or biogenic material (Sunamura, 1992); (2) eroded material from the platform itself (Trenhaile, 2001); and (3) onshore sources transported to the reef by waterways and wind (Sunamura, 1992).

The presence of sediment on a platform acts in two different ways. The first involves a fine sediment layer that causes scour to the platform surface (Sunamura, 1992). The second is a thick layer of sand that protects the platform surface from the effects of waves (Sunamura, 1992) and could be described as a perched beach. The volume and mean grain size of sediment on a platform varies as a result of exposure to wave energy, storminess, heavy wave action and runoff (Cassata and Collins, 2008; Littler *et al.*, 1983; Schiel *et al.*, 2006; Stewart, 1983). Platforms exposed to high wave energy will

have less sediment on them and in some cases none (Schiel et al., 2006). Furthermore, the mean grain size of sediment decreases with decreased wave energy (Schiel et al., 2006).

High Water Interface

The morphology of the high water interface varies considerably between countries, regions and platforms. As described by Griggs and Trenhaile (1994), Trenhaile (2000) and Sunamura (1992) shore platforms evolved from the erosion of cliffs (see Figure 34 in Appendix 2 – Detailed methods). This cliff may be completely eroded or covered by sand resulting in a variety of high water interface descriptions, including:

- *Relict upper level platform*- platform from mean sea level fluctuations including the last interglacial. Upper level platform may also be present with many other features described below.
- *Cliff*- any abrupt vertical change in the profile of the platform. Cliffs can be small in height but defined here as greater than 3 metres high.
- *Notch*- a cliff less than 3 metres that can be undercut by waves.
- *Perched beach*- a sandy beach overlain on rock platform where all physical forcings on the underlain platform are buffered by the sand.
- *Pocket beach*- similar to a perched beach but restricted by cliff like structures onshore and alongshore.

Although no classification of the high water interface exists for platforms, it is predicted that the features described above may help to describe difference in platform morphology at Ningaloo.

Methods

Wind Data

Due to limited existing knowledge of wind regimes throughout the study area, hour averaged wind speed and direction was obtained for two weather stations located within and in close proximity to the study area. Milyering is the northern station and closest to sites north of Coral Bay. Data from Milyering were provided by the Australian Institute of Marine Science for the period 1997 to present. Carnarvon weather station is south of the study area but closest for all remaining sites including those at Three Mile and Gnaraloo Bay. Data for Carnarvon was provided by the Bureau of Meteorology (BoM) for the period 1993 to present. The direction of the dominant and prevailing wind conditions for each station was determined through visual analysis of wind roses produced with all available wind data in the program WRPLOT View Version 5.9.

Analysis of extreme events was conducted by plotting the speed and direction of hourly wind data records from Milyering weather station exceeding 40km/hr. This information was compared with

cyclone information from BoM (2010) to identify how much of an influence cyclones have on the wind regime at Ningaloo and if the wind direction is from a consistent direction.

Field-Collected Data

Data collected in the field was conducted in three field trips (Table 5) with assistance from Jacob Loughridge, University of Western Australia and Cristina Da Silva, University of Western Australia. A number of physical variables were measured and the methods are described below.

Table 5: Field trips used to collect onsite shore platform data.

Field Trip	Sites	Data collected	Assistants
July 2009	Northern	<ul style="list-style-type: none"> • Medium and fine scale complexity • Platform attributes 	Jacob Loughridge
September 2009	Southern	<ul style="list-style-type: none"> • Sediment collection 	None
December 2009	All	<ul style="list-style-type: none"> • Profiling 	Cristina Da Silva

Profiling

Profiling was conducted using a Real-Time Kinematics (RTK) Differential Global Positioning System (DGPS). The profile transect began at the top of the primary dune and extended as far offshore as conditions and water level allowed ensuring the safety of the surveyor and electrical equipment. The profile was taken through the centre of the site and perpendicular to shore. All sites were profiled except Elle's Out and Elle's In due to the remoteness of the site and time constraints. Further details on profiling are attached in Appendix 2 – Detailed methods. Profiles were used to determine Complexity- Broad scale, Gradient and a number of platform dimensions.

Platform Surface Complexity

The complexity of the platform was collected at three scales, broad, medium and fine scale. Medium and fine scales were measured using lengths of galvanised chain laid over the contours of the substratum (Figure 5). Two different lengths and sizes of chains were used:

Medium- 740cm long chain with each link 19.8mm inside length, 7.4mm inside width and 4.9mm thick.

Fine- 200cm long chain with each link 16mm inside length, 6.1mm inside width, 2.6mm thick.

The chain was flattened to the contour of the platform by walking over it and ten measurements were taken approximately 5m apart for the entire length of the site. A complexity value was calculated as the ratio between the mean planar distance between the two ends of the chain and the known lengths of the chains (Figure 5). A mean complexity value was calculated from the ten values and used in the analyses. Broad scale complexity was measured using the profile information of the platform; defined as the area between the low tide cliff or furthest extent of a grading platform offshore and the base of the notch, ramp, or beach (Figure 5). The planar distances between each point recorded within this boundary were summed and divided by the total length of the platform. At all 3 scales of complexity the larger the value, the greater the complexity of the substratum.

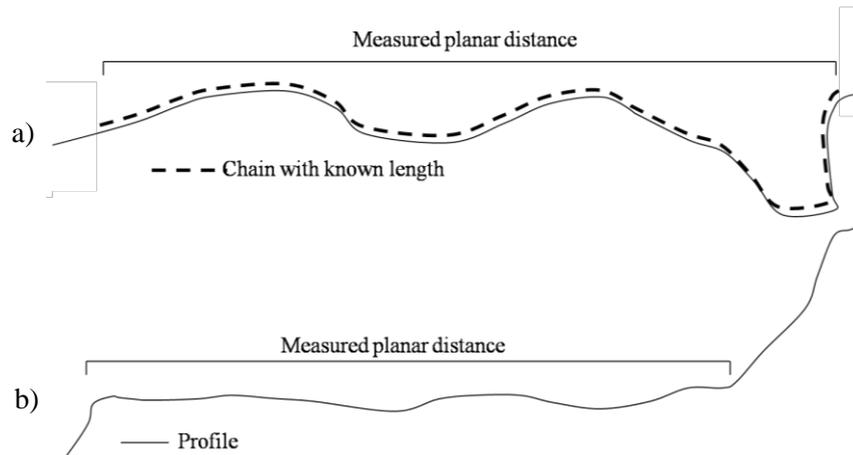


Figure 5: Methods of measuring the complexity a) fine and medium scales using the chain method b) broad scale complexity measured using profile data.

Platform Sediment

Three sediment samples were collected from throughout the site (Figure 6). Samples were collected from the surface of the platform and from small crevices. Each sample contained approximately 50 grams of wet sediment but varied depending on the availability. Samples were dried in an oven at approximately 60 °C for at least 48 hours. Settling velocities were calculated using a settling tube similar to that described by Kench & McLean (1996) and used to calculate the mean grain size and sortedness (Equation 1 and Equation 2 respectively).

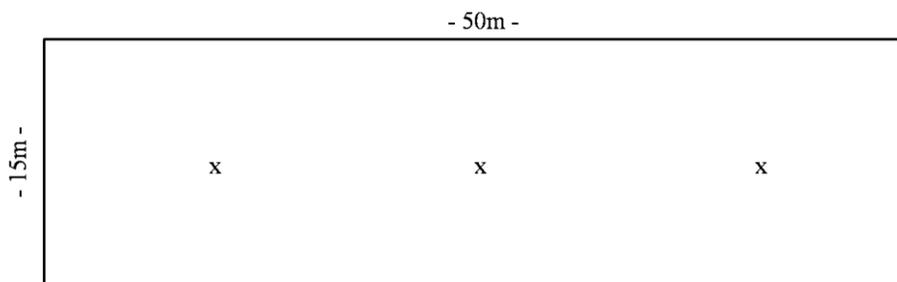


Figure 6: Approximate location of sediment sample collection (x).

Equation 1: Mean grain size calculated from cumulative fall velocities (Folk & Ward, 1957).

$$M_z = \frac{\phi 16 + \phi 50 + \phi 84}{3}$$

Equation 2: Sortedness (Folk & Ward, 1957)

$$\sigma_1 = \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6}$$

Platform Gradient

Platform gradient was calculated using the profile points between the low tide cliff or the furthest offshore extent of the profile for grading platform and the base of the notch, ramp or beach (Figure 7). A regression line and equation was calculated in Microsoft Excel and the arcsine value of m (the coefficient of x) was used to calculate the gradient in degrees.

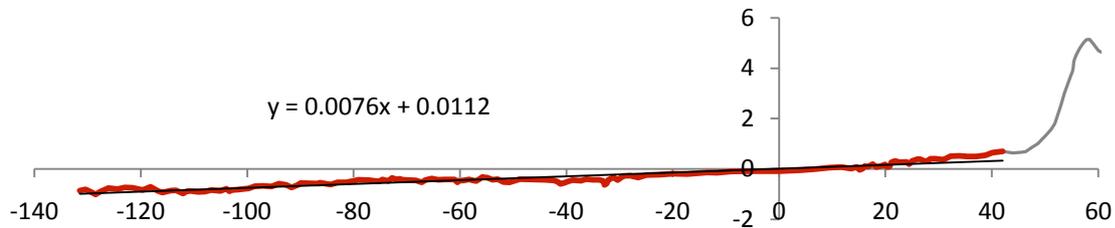


Figure 7: Extent of the profile where the gradient was calculated showing the regression line and its equation.

Platform Height

Platform height was calculated using measured onsite water level height relative to the platform and corrected using predicted tidal height and residual water level data collected at Exmouth and Carnarvon (provided by the Department of Transport). Further details of this method are in Appendix 2 – Detailed methods.

Platform Attributes

Key physical attributes of platforms were identified from a review of literature and many were found throughout the study site. Additional attributes were added to those identified in the literature as they were thought to be influencing processes impacting on the platform. Nine attributes were identified across eight sections of the profile (Figure 8). For an example of each platform attribute refer to *Platform Attributes* in Appendix 2 – Detailed methods.

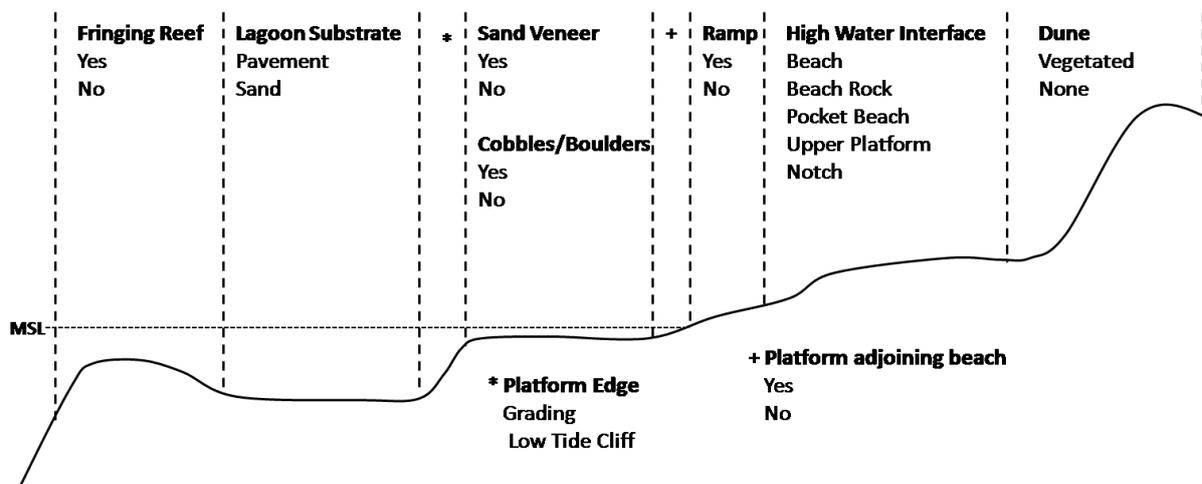


Figure 8: Attributes for each section of a typical profile extending from the fringing reef to the primary dune.

Desktop-Collected Data

Fetch

Fetch is defined as the distance and duration that wind can blow uninterrupted to develop wind waves. Larger waves form in areas with larger fetch lengths and longer blowing durations. Duration time that the wind blows is assumed constant throughout the study site. Fetch lengths were calculated in three directions, dominant² and prevailing³ wind direction, orthogonal to shore and in the longest fetch length direction. Fetch length was calculated as the distance from the site to the 1metre contour for the directions described. Location of the 1metre contour was identified from printed bathymetry maps produced in ArcMAP using hyperspectral imagery provided by W. Klonowski, Curtin University. Unlimited⁴ fetch lengths were given a value of 10000 metres.

Distance to 10 metre Contour

The distance from the site to the 10 metre contour was observed to vary significantly between sites, with smaller distances usually being associated with greater observed wave energy. It was thought to be a good indicator of lagoon width as fetch lengths would sometimes pass through small gaps in the reef and not truly represent lagoon dimensions. This distance was measured in the same three directions as fetch lengths but instead of longest distance for fetch, the shortest distance to the 10 metre contour was recorded.

Platform Width

The width of the platform at each site was calculated in a straight line perpendicular to the coastline passing directly through the study site from the landward extent of the platform to the seaward extent of the platform. The landward extent is defined as whichever of the following features occur furthest seaward: the base of the notch/cliff, the sandy beach – platform boundary or the top of the ramp. The seaward extent is defined as whichever of the following features (or combination of features) occur furthest landward; the low tide cliff, the interface where continuous platform changes to patch reef, the interface between platform and sand or any noticeable change in depth. Profile information, geo-rectified aerial photographs and bathymetry were used in combination to determine the location of the above features (Figure 9).

Aspect

Aspect was calculated as the direction of the transect used for profiling. This transect is perpendicular to the shoreline passing through the middle of the site.

² Dominant wind direction is that in which the strongest winds blow from.

³ Prevailing wind direction is that in which the wind most frequently blows from.

⁴ Fetch was deemed unlimited if it passed the average offshore distance of the fringing reef and entered water deeper than 20 metres.

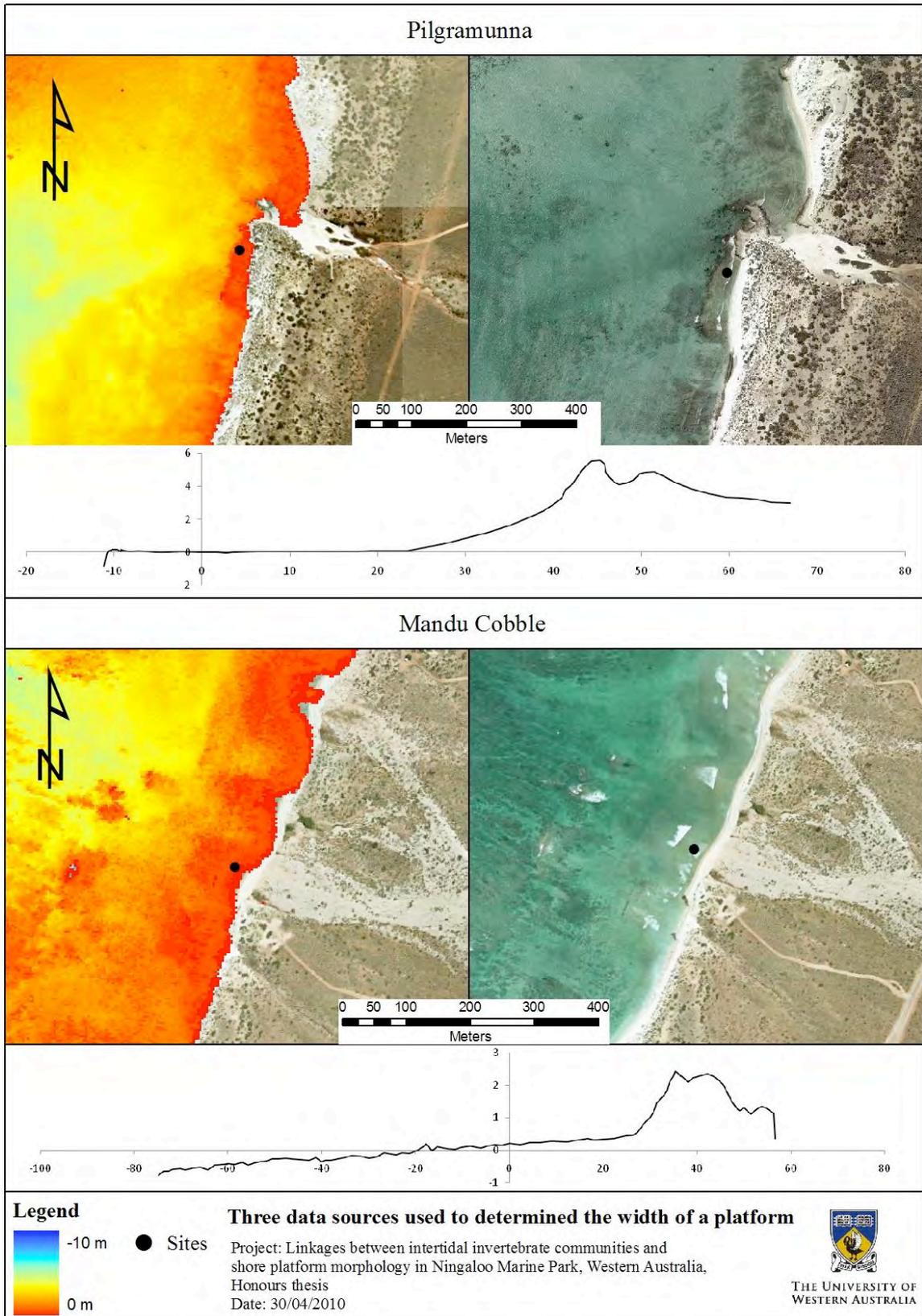


Figure 9: Three data sources 1) bathymetry, 2) geo-rectified aerial photographs and 3) profile information used to determine the width of a platform.

Coastal Heterogeneity

Coastal heterogeneity was recorded as the length of coastline⁵ across a 2 kilometre straight-line stretch of coast, 1 kilometre either side of the site (Figure 10). Measurements were done in ArcMap and Google Earth.

Offshore Reef Extent

From initial investigations of aerial photography and results of dominant and prevailing wind direction and fetch lengths, it was evident that the extent off shore reef would be measured across a wide length of reef. It was concluded that the extent of offshore reef would be measured in meters and across 10 kilometres of reef or the 10 metre contour. The midpoint of this 10 kilometre stretch was defined as the reef crest⁶ or 10 metre contour directly offshore from the site in the direction of the aspect of the site. Five kilometres of reef crest or 10 metre contour was measured from this point in either direction of the midpoint and the extent of reef crest was recorded. Measurements were done in ArcMAP using geo-rectified aerial imagery (Figure 11).

⁵ Coastline is defined as the water land boundary during the time that aerial imagery was taken.

⁶ Reef crest is the most seaward extent of a fringing reef and can be identified by depth of approximately 1 metre with a sharp increase in depth seaward.

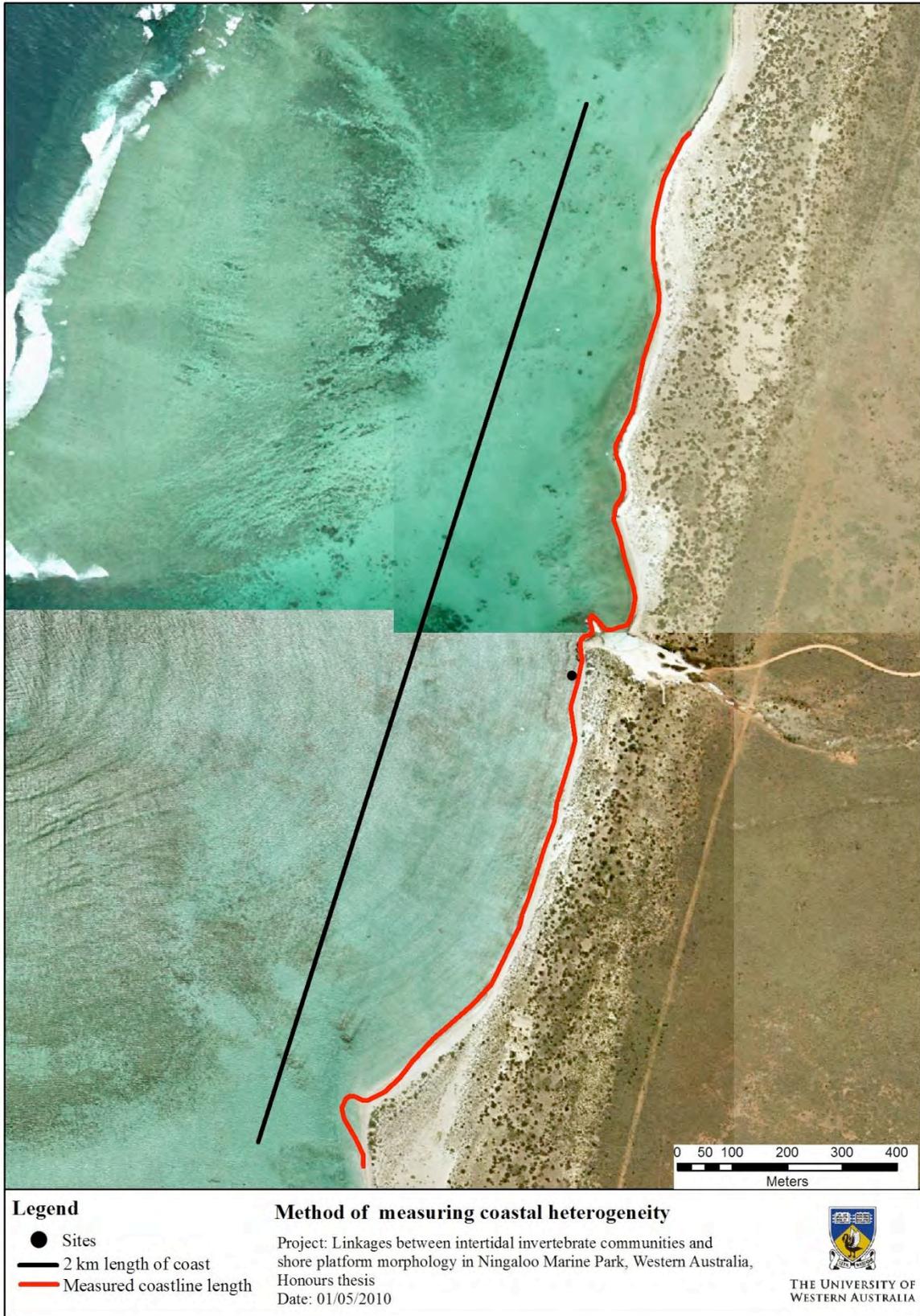


Figure 10: Method of measuring coastal heterogeneity in ArcMAP at Pilgramunna.

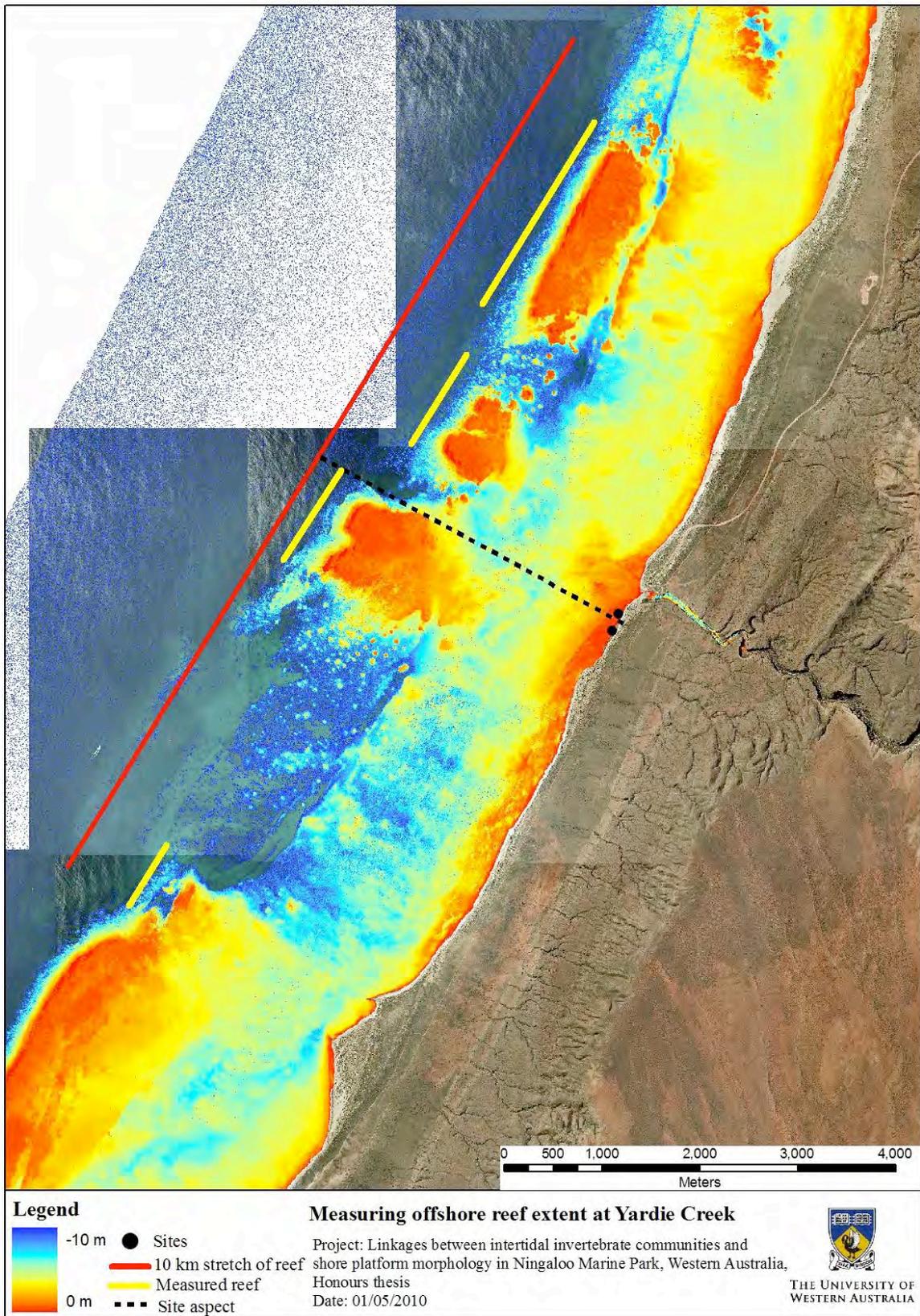


Figure 11: Method of measuring offshore reef extent in ArcMAP at Yardie Creek.

Identification of Morphotype Groups

The identification of platform morphotypes was determined from the clustering of dissimilarity values for each site similar to that described by Schoch and Dethier (1996) and Travers (2006). A dissimilarity matrix was calculated in the statistical program *R* using the statistical package *Cluster*. Data were standardised (mean=0 and standard deviation=1) and the dissimilarity matrix computed using Gower's similarity coefficient, which is capable of handling missing values and mixed data. A number of clustering methods, both hierarchal and agglomerative, were considered but the PAM (Partitioning Around Medoids) method was deemed most appropriate for this analysis. The algorithm used in PAM is based on the search for k (user defined) representative samples within the data (medoids) (Kaufman & Rousseeuw, 1990). Once medoids have been established the remaining samples are clustered around these. This method must be used carefully as even completely random data can be clustered together. Experimenting with different numbers of cluster groups assisted in determining how many morphotype groups would be used.

To test the importance of spatial scale and sampling methods (onsite measurements verses desktop methods) and to further investigate variables determining each cluster, subsets of the data were created (Table 6). Inconsistent cluster results using different numbers of clusters and different datasets resulted in the formation of the final dataset titled *Essential*. The Essential dataset included the key variables traditionally used to investigate rocky coast morphology. This dataset produced consistent cluster groups using PAM and was chosen as the dataset appropriate to describe potential morphotypes.

Table 6: Variables included in each set of data used for investigative clustering.

Dataset	Height	Gradient	Complexity-broad	Complexity-medium	Complexity-fine	Mean sediment size	Sediment sortedness	Width	Offshore reef extent	Coastal heterogeneity	Aspect	10m contour- dominant/ prevailing	10 contour- orthogonal	10m contour- smallest	10m contour- direction of smallest	Fetch- dominant/ prevailing	Fetch- orthogonal	Fetch- longest	Fetch- direction of longest	Fringing reef	Dominant lagoon substrate	Platform edge	Platform all the way to shore	Ramp	High water interface	Dunes	Cobbles and boulders	Sand veneer	
All	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Desktop								X	X	X	X	X	X	X	X	X	X	X	X	X	X								
Onsite	X	X	X	X	X	X	X															X	X	X	X	X	X	X	X
Platform attributes																				X	X	X	X	X	X	X	X	X	X
No platform attributes	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X										
Fetch												X	X	X	X	X	X	X											
No fetch	X	X	X	X	X	X	X	X	X	X	X									X	X	X	X	X	X	X	X	X	X
Essential	X	X		X	X			X	X											X		X		X			X		

Data of the Essential dataset were transformed to ensure the distribution was close to normal and a PAM cluster analysis was undertaken on the transformed data (Table 7). A description of each morphotype was then developed from a summary of the cluster results and a schematic developed to illustrate each morphotype.

Table 7: Transformations used on the *Essential* dataset.

Variable	Transformation
Height	$\text{Ln}(X+1)$
Gradient	$\text{Log}(X+1)$
Complexity- medium	$\text{Arcsin}(X)$
Complexity- fine	$\text{Arcsin}(X)$
Offshore reef extent	None
Width	$\text{Ln}(X)$
Platform edge	None
Fringing reef	None
Cobbles and boulders	None

Results

Wind Analysis

Annual wind rose plots for Milyering weather station and Carnarvon weather station are displayed in Figure 12 and Figure 13 respectively. Monthly wind rose plots were produced using daily wind data and seasonal wind rose plots were produced using daily, 9am and 3pm wind records are attached in Appendix 3 – Wind roses.

The dominant wind direction at Milyering weather station is south west during summer (3pm) and south east in autumn (9am), winter (9am) and spring (9am). Prevailing winds are south westerly, prevailing all day in summer and spring, whilst being more common in the afternoon (3pm) during winter and autumn. For the purpose of this project and measuring fetch and with the knowledge that all sites are protected from dominant south east winds, sites closest to Milyering weather station will be referred to as having both dominant and prevailing winds from the south west.

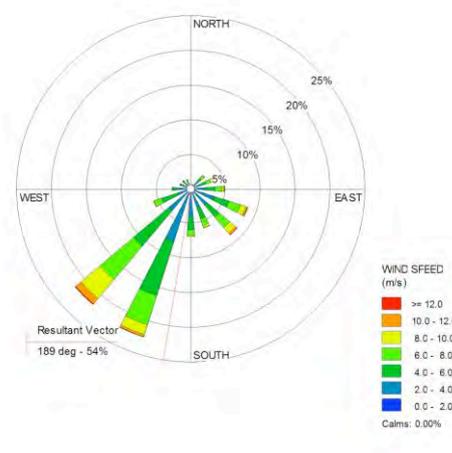


Figure 12: Annual wind rose plot for the Milyering weather station (1997-present). Data source: AIMS, 2010.

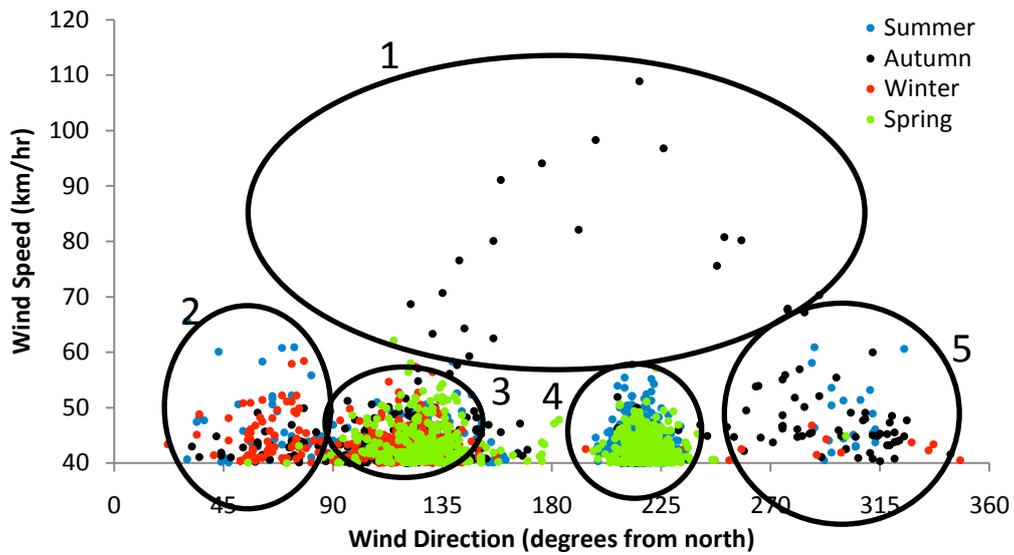


Figure 14: Scatter plot of all hourly wind records exceeding 40kmhr^{-1} for Milyering weather station (1997-current). Data sourced: AIMS, 2010. 1) Tropical Cyclone Vance, 2) North easterly winds, 3) combination of Cyclone influences and easterly morning winds, 4) south westerly sea breeze systems and 5) Tropical cyclone influences.

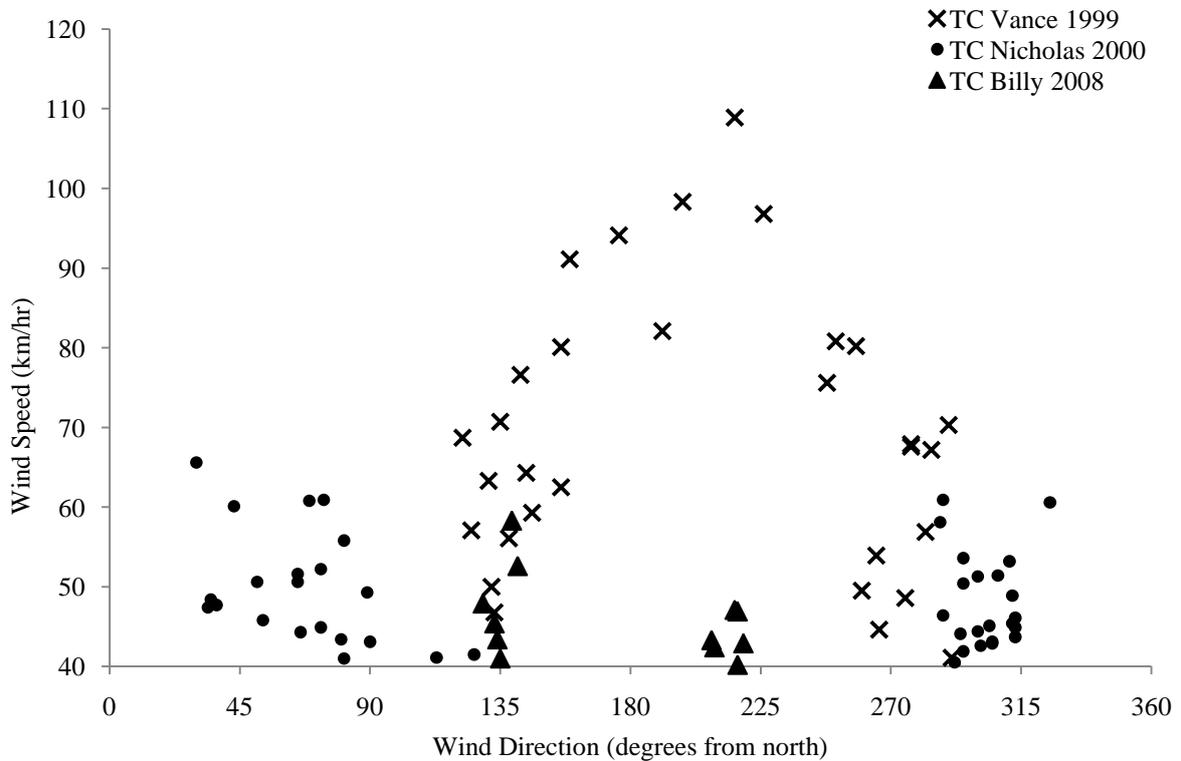


Figure 15: Hourly mean wind direction and speed records above 40km/hr recorded for three major tropical cyclones at Milyering weather station.

Platform Analysis

Raw data for all variables measured in the field and from desktop methods excluding fetch data and platform attribute data are in Table 8. Fetch data and distances to the 10 metre contour are in Table 9 and platform attribute data are in Table 10. Profile plots are attached in Appendix 4 – Site profiles. Sediment cumulative plots are presented in Appendix 5 – Sediment grain size distribution plots..

Initial investigation into the raw data identified that some variables differed between sites particularly from north to south. It was also evident that some sites were similar in some variables but different in others. This initial first pass visual analysis of the raw data combined with an investigation into any correlation between variables lead to the development of the subsets of data. It was clear that many of the fetch variables were correlated to one another as well as the platform attribute data and lead to their separation in further clustering. As a result, a number of different cluster groups were investigated with different sub sets of the data and the results are presented in Table 11. These results show that the data used and the number of defined clusters alters the groupings of sites. For the majority of cluster analyses, it was decided that the ideal number of cluster groups would be 7 as this produced groups with a relatively even number of sites and provided consistently good results. However, with a reduced number of variables used in the Essential subset of data, 5 cluster groups were believed to provide the best representation of this data.

From visual analysis of all clustering results (Table 11) it was evident that some sites were continually grouped together regardless of what dataset was used. The *Essential* dataset with 5 clustering groups was believed to best represent all the cluster results and the observed and recorded morphological difference between the sites under investigation. A summary of the results for each morphotype was subsequently produced from the raw data (Table 12). Column graphs displaying the results of each of the variables used in the Essential dataset for each site are attached in Appendix 6 – Platform variable charts.

Table 8: Results for those variables measured onsite and from desktop methods. NR: Not recorded, NS: No sediment.

Site	Height (m)	Gradient (°)	Width	Complexity-broad	Complexity-medium	Complexity-fine	Mean sediment grain size (phi)	Sortedness	Offshore reef extent (m)	Coastal Heterogeneity (m)
MW	0.693	0.430	185	0.9990	0.973	0.953	1.813	0.448	233	2818
MWW	0.332	0.097	205	0.9995	0.965	0.959	0.771	0.578	233	2677
SN	0.422	0.424	140	0.9972	0.961	0.908	0.580	0.583	233	2507
SS	0.504	0.241	143	0.9989	0.960	0.953	0.623	0.728	233	2050
JO2	0.661	0.103	88	0.9996	0.974	0.924	0.375	0.552	2170	2139
JO1	0.534	0.418	91	0.9977	0.968	0.941	0.682	0.794	930	2143
JI1	0.595	-0.172	82	0.9918	0.964	0.925	0.573	0.651	2790	2133
JI2	0.582	0.143	139	0.9968	0.960	0.954	1.293	0.471	3255	2149
JI3	0.350	0.183	160	0.9943	0.964	0.936	1.169	0.401	3720	2139
MB	0.775	0.722	74	0.9954	0.939	0.854	1.239	0.739	9920	2759
MP	0.588	0.057	220	0.9984	0.956	0.895	0.643	0.648	9300	3047
MC	0.799	0.613	90	0.9990	0.947	0.846	0.700	1.055	4960	2090
MF	1.089	0.286	100	0.9963	0.964	0.897	2.154	0.537	9688	2105
PIL	0.651	0.052	31	0.9950	0.981	0.957	0.293	0.604	9300	2246
YCN	0.979	0.533	145	0.9993	0.954	0.919	0.732	0.931	4650	2148
YCS	1.020	0.435	225	0.9970	0.954	0.886	1.509	0.603	4805	2124
BBO2	0.592	0.292	220	0.9997	0.962	0.879	1.341	0.396	6045	2112
BBO1	0.624	0.223	160	0.9988	0.900	0.835	-0.025	0.693	6820	2286
BBI	0.535	0.189	104	0.9999	0.943	0.844	0.881	0.433	5580	2425
CBN	0.823	0.086	29	1.0000	0.956	0.885	1.141	0.593	7905	2236
CBS	0.706	0.387	25	0.9995	0.956	0.894	0.750	0.708	7905	2218
EI	0.703	NR	143	NR	0.960	0.967	0.940	0.331	6510	2248
EO	0.518	NR	80	NR	0.962	0.876	0.481	0.490	6355	2272
GBO2	0.629	0.705	42	0.9873	0.966	0.949	0.696	0.973	2790	2072
GBO1	1.012	0.252	45	0.9954	0.970	0.886	NS	NS	2868	2112
GBI2	0.760	0.120	91	0.9978	0.930	0.811	0.747	0.931	3255	2644
GBI1	0.735	0.521	63	0.9960	0.980	0.952	1.287	0.863	3410	2555
3MI3	0.663	0.011	201	0.9962	0.937	0.798	0.565	0.466	6278	2125
3MI2	0.778	1.323	37	0.9900	0.914	0.936	0.652	0.326	5193	2162
3MI1	1.265	0.286	28	0.9777	0.918	0.933	NS	NS	5193	2158
3MO1	1.695	0.000	35	0.9752	0.908	0.934	0.263	0.373	5193	2168
3MO2	0.478	0.378	36	0.9994	0.974	0.968	NS	NS	4883	2129

Table 9: Results of fetch and distance to the 10 metre contour measured from desktop methods. All distance are displayed in meters and directions described in 22.5 degree intervals.

Site	Aspect	Fetch (m)				10m Contour (m)			
		Prevailing	Orthogonal	Longest fetch	Longest fetch direction	Prevailing	Orthogonal	Smallest distance	Smallest distance direction
MW	NNE	0	100000	100000	NNE	100000	1178	1132	N
MWW	NNW	0	100000	100000	NNW	100000	1628	1209	NW
SN	NW	0	100000	100000	NW	100000	1039	930	NW
SS	N	0	100000	100000	N	100000	1008	822	NW
JO2	NNE	0	100000	100000	NNE	100000	1876	977	NW
JO1	NNW	0	100000	100000	NNW	100000	899	899	NNW
J11	NNW	0	100000	100000	NNW	100000	1008	853	N
J12	NNW	2620	1550	1550	NNW	100000	1349	1070	N
J13	NW	2232	100000	100000	NW	100000	1674	1271	N
MB	NW	4371	2883	100000	NNE	5580	3705	2976	WNW
MP	WNW	4325	2046	2046	WNW	5503	3131	3131	WNW
MC	WNW	744	100000	100000	WNW	1969	1225	853	WNW
MF	WNW	543	100000	100000	WNW	1984	977	899	WNW
PIL	WNW	2093	100000	100000	WNW	3240	1442	1442	WNW
YCN	WNW	8990	2356	100000	NNE	10308	2790	2573	WSW
YCS	WNW	9130	2170	100000	WSW	10230	3178	2620	WSW
BBO2	W	13020	100000	100000	WSW	1473	1132	1023	W
BBO1	WNW	12633	5580	100000	W	1519	961	915	WSW
BBI	NNW	0	100000	100000	NNW	100000	1054	1054	NNW
CBN	WNW	2124	2248	100000	NW	3023	2868	2449	W
CBS	WNW	1783	2093	100000	NNE	2697	2465	2279	W
EI	W	310	100000	100000	W	620	481	481	W
EO	W	0	0	0	W	853	341	341	W
GB02	NW	0	100000	100000	WNW	100000	1085	868	WNW
GB01	NW	0	100000	100000	SW	100000	1721	853	NNW
GBI2	NW	0	100000	100000	WNW	100000	1085	930	NW
GBI1	NNW	0	100000	100000	NNW	100000	1070	1008	NW
3M13	W	233	186	100000	W	4340	543	543	W
3M12	NW	0	100000	100000	NW	100000	450	450	NW
3M11	NW	0	100000	100000	NW	100000	419	419	NW
3M01	NW	0	100000	100000	NW	100000	403	403	NW
3M02	NW	0	100000	100000	NW	100000	698	434	NW

Table 10: Platform attributes. * HWI= High Water Interface, B= Beach, BR= Beach Rock, PB= Pocket Beach, UP= Upper Platform, N= Notch.

Site	Fringing reef	Predominant lagoon substrate	Platform edge	Platform joined to shore	Ramp	*HWI	Dunes	Cobbles or boulders	Sand veneer
MW	None	Pavement	Grading	Yes	Yes	B	Vegetated	No	Yes
MWW	None	Pavement	Grading	Yes	No	B	Vegetated	No	Yes
SN	None	Pavement	Grading	Yes	No	BR	Vegetated	No	Yes
SS	None	Pavement	Grading	Yes	No	PB	Vegetated	No	Yes
JO2	None	Pavement	Low Tide Cliff	Yes	Yes	N	Vegetated	No	Yes
JO1	None	Pavement	Grading	Yes	Yes	BR	Vegetated	No	Yes
J11	None	Pavement	Grading	Yes	No	B	Vegetated	No	Yes
J12	None	Pavement	Grading	Yes	Yes	BR	Vegetated	Yes	Yes
J13	None	Pavement	Grading	Yes	Yes	UP	Vegetated	Yes	Yes
MB	Continuous	Sand	Grading	No	No	B	Vegetated	No	Yes
MP	Continuous	Sand	Grading	Yes	No	UP	None	No	Yes
MC	Discontinuous	Pavement	Grading	Yes	No	B	None	Yes	Yes
MF	Discontinuous	Pavement	Grading	Yes	No	PB	Vegetated	No	Yes
PIL	Discontinuous	Sand	Low Tide Cliff	Yes	No	B	Vegetated	Yes	Yes
YCN	Discontinuous	Pavement	Grading	Yes	No	B	Vegetated	Yes	No
YCS	Discontinuous	Pavement	Grading	Yes	No	B	Vegetated	Yes	No
BBO2	Discontinuous	Sand	Grading	Yes	Yes	B	Vegetated	No	Yes
BBO1	Discontinuous	Sand	Low Tide Cliff	Yes	Yes	BR	Vegetated	No	Yes
BB1	Discontinuous	Sand	Grading	Yes	Yes	B	Vegetated	No	Yes
CBN	Continuous	Pavement	Low Tide Cliff	Yes	Yes	UP	Vegetated	No	Yes
CBS	Continuous	Sand	Low Tide Cliff	Yes	Yes	N	Vegetated	No	Yes
E1	Discontinuous	Sand	Low Tide Cliff	Yes	No	B	Vegetated	No	No
E0	Discontinuous	Pavement	Grading	No	No	B	Vegetated	No	Yes
GB02	None	Sand	Grading	Yes	Yes	UP	Vegetated	No	Yes
GB01	None	Sand	Low Tide Cliff	No	No	B	Vegetated	No	Yes
GB12	Discontinuous	Pavement	Grading	Yes	No	B	Vegetated	No	Yes
GB11	Discontinuous	Pavement	Grading	Yes	Yes	B	Vegetated	No	Yes
3M13	None	Pavement	Grading	Yes	Yes	B	Vegetated	No	Yes
3M12	None	Pavement	Low Tide Cliff	Yes	No	N	Vegetated	No	No
3M11	None	Pavement	Low Tide Cliff	Yes	No	N	Vegetated	No	No
3M01	None	Pavement	Low Tide Cliff	Yes	No	N	Vegetated	No	No
3M02	None	Pavement	Grading	Yes	Yes	N	Vegetated	No	No

Table 11: Cluster group results for different datasets using the PAM method of clustering in the R Statistical package Cluster.

Data used	All		Desktop		Onsite		Platform attributes		No platform attributes		Fetch		No fetch		Essential		Essential transformed	
	7	7	7	7	7	7	7	7	7	7	7	7	5	7	5	7	5	
Site	MW	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	MWW	2	1	2	2	1	1	1	2	1	2	1	2	1	2	1	2	1
	SN	2	2	2	2	1	2	1	2	1	2	1	2	1	2	1	2	1
	SS	2	2	2	2	1	2	1	2	1	2	1	2	1	2	1	2	1
	JO1	1	1	3	1	2	1	2	1	1	2	1	1	1	1	1	1	1
	JO2	1	2	4	1	1	2	2	1	1	2	1	1	1	1	1	1	1
	J11	1	1	2	2	2	1	1	2	1	2	1	2	1	2	1	2	1
	J12	1	1	3	1	2	3	2	1	1	2	1	1	1	1	1	1	1
	J13	2	2	3	1	1	2	2	1	1	2	1	1	1	1	1	1	1
	MB	3	3	5	3	3	4	3	3	3	4	3	3	2	3	2	3	2
	MP	3	4	2	2	4	5	3	2	3	2	3	2	3	2	2	2	2
	MC	4	5	6	4	5	6	4	4	4	4	4	4	4	4	4	3	3
	MF	4	5	2	2	5	6	4	4	4	4	4	4	4	4	4	3	3
	PIL	4	5	2	5	5	6	5	5	4	5	5	4	5	4	5	3	3
	YCN	5	6	6	2	4	4	4	4	4	4	4	4	4	4	4	3	3
	YCS	5	6	6	2	4	4	4	4	4	4	4	4	4	4	4	3	3
	BBO2	6	7	1	6	6	6	6	6	6	6	6	2	3	2	3	2	2
	BBO1	3	6	4	6	4	7	5	6	2	6	2	3	2	3	2	2	2
	BBI	1	1	1	6	2	1	6	6	2	6	2	3	2	3	2	2	2
	CBN	3	3	4	1	3	7	5	3	3	3	3	6	4	6	4	4	4
	CBS	3	3	4	6	3	4	5	3	3	3	6	4	6	4	4	4	4
	EI	6	7	5	5	6	7	6	5	2	5	2	5	2	5	2	2	2
	EO	6	7	5	3	6	7	6	5	4	5	3	5	3	5	3	3	3
	GBO2	1	2	1	6	1	6	2	1	1	1	1	1	1	1	1	1	1
	GBO1	2	2	5	3	2	1	3	7	5	7	5	7	5	7	5	5	5
	GBI2	2	2	2	2	1	2	3	6	2	3	2	3	2	3	2	2	2
	GBI1	1	1	1	6	2	1	2	1	1	1	1	1	1	1	1	1	1
	3MI3	6	7	1	1	6	7	6	6	2	3	2	3	2	3	2	2	2
	3MI2	7	2	7	7	7	2	7	7	5	7	5	7	5	7	5	5	5
	3MI1	7	2	7	7	7	2	7	7	5	7	5	7	5	7	5	5	5
	3MO1	7	2	7	7	7	2	7	7	5	7	5	7	5	7	5	5	5
	3MO2	7	2	1	1	1	2	2	1	1	1	1	1	1	1	1	1	1

Table 12: Summary of variables for each morphotype.

Morphotype	Sites	Height (m)	Gradient	Complexity-medium (cm)	Complexity-fine (cm)	Offshore reef extent (%)	Width (m)	Platform edge	Ramp	Fringing reef	Cobbles and boulders	Sand veneer
1	MW, MWW, SN, SS, JO1, JO2, JI1, JI2, JI3, GBO2, GB1, 3MO2	<0.8	Variable	710-730	180-195	<50	30-210	Grading	Yes	None	Some	Yes
2	MB, MP, BBO2, BBO1, BBI, EO, GBI2, 3MI3	0.5-0.8	Variable	660-710	160-180	30-100	70-220	Grading	50%	Continuous and discontinuous	None	Yes
3	CBN, CBS	0.6-0.8	Variable	710	175-180	80	<50	Low tide cliff	Yes	Continuous	None	Yes
4	MC, MF, PIL, YCN, YCS, EI	0.6-1.1	Variable	700-730	170-195	50-100	30-230	Grading and low tide cliff	No	Discontinuous	Yes	Yes
5	GBO1, 3MI2, 3MI1, 3MO1	0.8-1.7	Variable	670-720	175-190	30-50	<50	Low tide cliff	No	None	None	No

Morphotypes

From these results a general description of each morphotype is essential for the current and future classification of shore platforms at Ningaloo. This description is based on clustering results which proved to be an essential explorative tool in identifying key variables and the groupings of sites. A schematic of each morphotype is displayed in Figure 16.

Morphotype 1 is characterised by a grading platform with little to no fringing reef. The complexity is smooth at medium and fine scale complexity measurements and many will have a ramp. The width of this platform is variable ranging from very narrow (30m) to very wide (210m). The majority of sites with this morphotype are located in the far north of the study site.

Morphotype 2 is characterised by a grading platform at mean height. This platform is complex at both scales but particularly complex at the fine scale. The width is variable with medium (70m) to wide platforms (220m) and the fringing reef can be both continuous and discontinuous. No boulders or cobble are found on the platform but half are expected to have a ramp present.

Morphotype 3 is characterised by a narrow (<50m) platform enclosed by continuous fringing reef with a low tide cliff. This platform has a ramp and its height is similar to morphotype 2. The complexity is medium at both scales and no cobbles or boulders are present.

Morphotype 4 is characterised by a relatively high platform with a discontinuous offshore reef. Like morphotype 1 this platform's complexity is low at both scales producing a smooth surface and of varying width from very narrow (30m) to very wide (230m). The platform edge is variable with both low tide cliffs and grading platforms present. The key difference in this platform is the presence of boulders and or cobbles.

Morphotype 5 is distinct from all other morphotypes. It is characterised by a relatively high platform that terminates with a low tide cliff. Medium scale complexity is relatively high due to presence of large rock pools but the fine complexity is relatively low resulting from a smooth platform surface. This platform is very narrow (<50m) with little offshore reef. There is no ramp, boulders or cobbles on this platform. This platform is characterised by a notch.

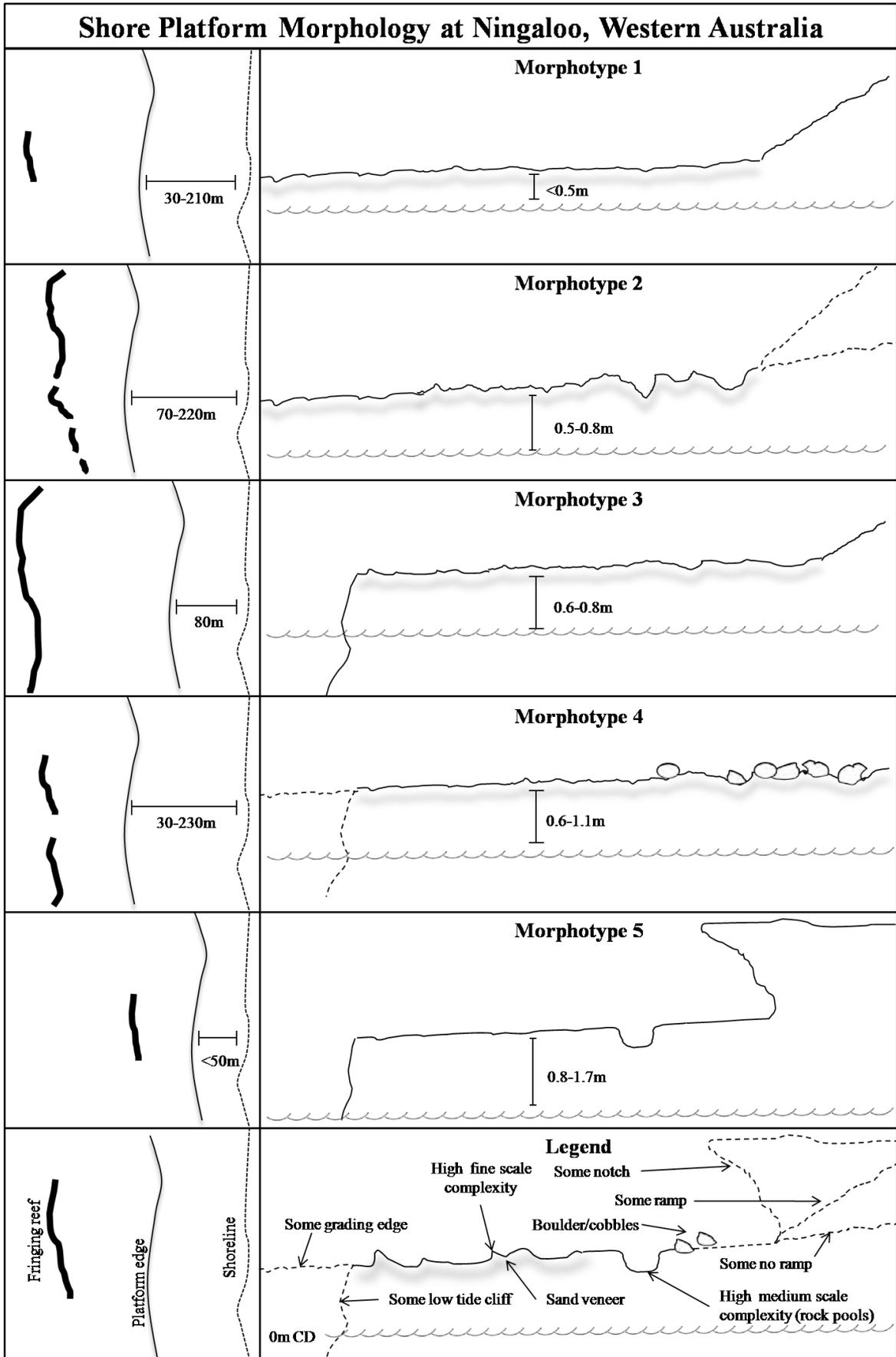


Figure 16: Schematic of platform morphotypes at Ningaloo.

Discussion

The differences in platform morphology at Ningaloo are large making the identification of similarities among sites difficult. When considering all possible differences between sites no two are the same and all platforms at Ningaloo could be considered as a continuum. It is only when the simple morphological differences between sites are considered that the defining boundaries in this continuum can be set. Although these boundaries or morphotypes do not include all sites in Western Australia or even Ningaloo, they provide a basis for further investigation into shore platform morphology and an example of the methods that can be used to classify this type of rocky coast.

Development of Morphotypes

As described by Schoch and Dethier (1996) using a clustering method that requires a predefined number of clusters could be misleading as even completely random data will be grouped together. Cluster analyses should be used as an investigative tool to assist in identifying trends in the data. The cluster results returned in this project further emphasise these points. All clustering results were different and dependent on the clustering method used, the sub set of data used and the number of clustering groups defined. The combination of raw data, experimenting with various clustering methods and only using a limited number of variables allowed groups of sites to be identified and morphotypes developed.

Furthermore, cluster results using broad or fine scale data sets were different and would have resulted in different morphotypes. One scale of variables cannot be substituted for the other and all methods should be considered when developing a classification of shore platforms.

Platform Height- the difference in two extremes

Elevation is described as one of the most important morphological aspects of platforms (Trenhaile, 1978; Sunamura, 1991; Trenhaile et al., 1999) and was a key variable used to develop morphotypes in this project. Elevation helped isolate sites that appeared morphologically different. Such sites included those at Three Mile (3MI2, 3MI2 and 3M01) and one site at Gnarlou Bay (GBO1) and were all classified as morphotype 5. Morphotype 5 was characterised with the highest elevation and had a narrow platform that terminated into a low tide cliff with little protection from swell waves. The limited offshore reef extent, the deep offshore bathymetry and the low tide cliff resulted in swell waves breaking directly on this platform as opposed to offshore and reaching the platform already broken. Homma & Horikawa, (1965) and Sunamura (1973; 1975) described similar results and suggested that platforms cut by breaking waves may be at higher elevations than those produced by broken waves. In comparison, morphotype 1 had the lowest elevation and therefore was expected to have continuous offshore reef protecting against swell wave energy but this is not the case. Morphotype 1 is characterised by little to no offshore reef, rather a grading platform morphology and

expansive shallow pavement terrace that assists in shoaling waves before they reach the platform resulting in the reduced elevation.

Platform Attributes

Ramp

Ningaloo has a high diversity of platform attributes recorded in the literature. Ramps for example have been described to occur in low tide swell dominated environments (Trenhaile & Layzell, 1981) as they are shaped by the high energy events that reach the upper limits of the intertidal. However, ramps are defining features in morphotype 1 and 3 which have different offshore reef extent and subsequent wave regimes. Morphotype 1 has no fringing reef while morphotype 3 has continuous fringing reef. It is hypothesised that higher than normal waves are experienced at both morphotypes causing an increased gradient at the shoreward margin of the platform. A key difference not identified by the presence or absence of the ramp was its width and complexity. Ramps present at the sites of morphotype 1 are wider with a more complex structure than those seen in the sites of morphotype 3. This may be due to the exposure of the site and the extent of offshore reef. Morphotype 3 has continuous reef that attenuates considerable amounts of swell energy (Sanderson, 2000) but also has a wide lagoon that has the capability of developing high energy short period wind waves particularly during sea breeze conditions. It is these short period wind waves that disturb the usually protected shore and reach the upper limits of the intertidal platform creating a small and narrow ramp. This may be able to explain why some sites in morphotype 2 have ramps and others do not, potentially because of the width of the lagoon and its increased ability to develop short period wind waves. In contrast, it is hypothesised that the wider ramps present in morphotype 1 are shaped by more “traditional” processes such as swell and storm waves. The more complex sections of the ramps are present further up the ramp and are likely to be a result of splash from waves hitting the bottom of the ramp.

Low Tide Cliff vs Grading Platforms

Sunamura (1992) suggested that the low tide cliffs rarely erode as evident from the large amount of biological build up on the face of the cliff even after severe storm waves. A number of sites at Ningaloo have extensive coral structures at the base and on the face of the low tide cliff suggesting that they are not retreating. In addition to the erosional development of grading platforms described by Sunamura (1992), Griggs and Trenhaile (1994), Trenhaile (2000) and others, it is predicted that this coral growth has the potential to transform a low tide cliff into a grading platform (Figure 17). Under the right conditions coral growth is expected to remain constant turning the low tide cliff into a steep living coral ramp. In time the ramp would extend, cement and produce a continuous grading pavement. It is hypothesised that platforms at Ningaloo are at different stages of this development. Four of the five sites at Jurabi have appeared to have already lost a clearly defined low tide cliff to

extensive offshore coral growth, while Pilgramunna has the initial stages of a living coral reef ramp (Figure 18).

This theory raises the issues of platform development during past changes in sea level and future projections of sea level rise. And if reduced coral growth in the future will result in more platforms with low tide cliffs. There needs to be further investigation into the presence and stage of development of a low tide cliff and platform width at Ningaloo to fully understand this theory.

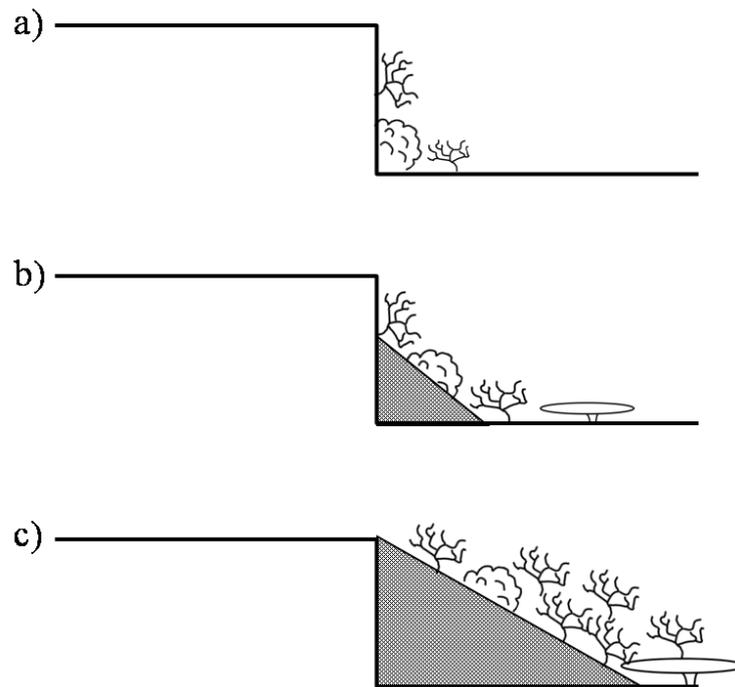


Figure 17: Reef building on the face and at the bottom of the tide cliff developing a grading edge of cemented and alive coral structures. Sites at development stage a) Pilgramunna, Coral Bay South and North; b) Jurabi Out 2; c) Jurabi Out 1, 2, 3 and 3 Mile Out 2.



Figure 18: Coral growth at the edge of the low tide cliff at Pilgramunna.

Complexity

Complexity is not traditionally used to describe platform morphology but considerably differs among morphotypes developed in this project. The differences in fine scale complexity recorded at Ningaloo are believed to be indicative of the amount of eroded or partially eroded material on the platforms' surface. Sites with highly complex surfaces crunch under the weight of a person and generally have fine silt across their surface. This suggests that the level of wave energy on this platform is low, as the eroded material has not been removed and the surface is fragile to physical forces. These observations could also suggest that the erosion of the platform is not due to wave energy but some other forcing such as bio-erosion or chemical erosion. It is important to note that sites with complex surface (Bateman Bay Out 1 and 2) have a grading edge, extensive offshore reef and are very wide. In contrast, sites with relatively smooth surfaces at the fine scale (3 Mile Out 1 and 2 and 3 Mile In 2) have bare rock with no silt layer and greater exposure to wave energy as a result of the low tide cliff, narrow platform and little offshore reef. It is hypothesised that this greater exposure is responsible for removing eroded material and smoothing the platform surface.

Medium scale complexity was used to quantify changes in platform surface topography such as rock pools. The method used, did pick up observed differences in complexity between morphotypes but it is not clear from the results which sites had more rock pools than others. This may be because sites with deep rock pools also had flat and smooth surfaces and therefore when averaged, had a similar value to sites with a generally complex surface (Figure 19). A better method to understand the presence of rock pools from medium scale complexity values would be to calculate the standard error of all ten measurements for a site. Sites with a high standard error are likely to have rock pools with a smooth surface.

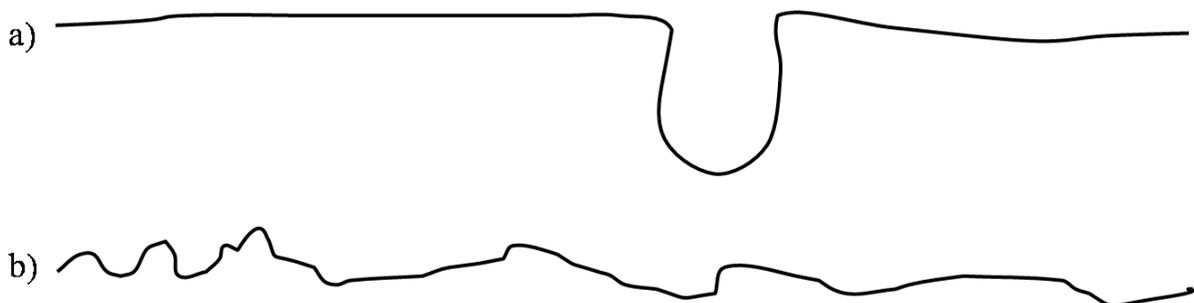


Figure 19: Different surface topographies that return the same medium complexity values. Sites a) with smooth flat surface and rock pools- 3 Mile In 1 and 2 and 3 Mile Out 1; b) consistently complex platforms with no deep rock pools- Bateman Bay Out 1.

Like medium scale complexity, broad scale complexity was used to determine large scale topographic differences of the platform, particularly changes in gradient and the presence of large pools. Although this method did identify some differences among sites these were not as pronounced as predicted. It is believed that this method is an accurate way to measure broad scale complexity but the sites selected for this project were too similar and therefore no considerable difference was identified. To

improve this method it is recommended that a regression line be fit to the profile of the platform and the vertical distance from each point to the regression line be calculated then divided by the number of points used. This method was not used in this project due to limited time and to retain consistency in the method of calculating complexity indices for the three different types of complexity.

Fetch

It was evident from the first pass analysis of aerial imagery that the presence and extent of offshore reef was likely to be the main driver for physical differences among sites as it controls the majority of processes the coastline experiences (see Sanderson, 2000). However, issues arose when trying to quantify this difference with the little information and time available. Fetch lengths were chosen as they identified the presence of offshore reef and the distance to that offshore reef and were easily calculated from bathymetric charts. The direction of the fetch measurement used was indicative of the prevailing and dominant wind conditions providing both the most common direction of waves and the “worst case scenario” of high energy waves. However, fetch lengths provided an inaccurate reflection of a site’s observed exposure to wave energy as some measurements passed through small gaps in the reef resulting in a relatively well protected site being recorded as having unlimited fetch. Conversely, some sites with no fringing reef had a slightly north west aspect that recorded very small fetch lengths as the coastline just protected them. As a result all fetch lengths and directions recorded were removed from the final analysis and determination of morphotypes as they provided little to no representative content. Offshore reef extent is believed to be indicative of observed wave exposure at Ningaloo and preferred over fetch lengths.

An accurate method of fetch or exposure is recommended for future studies at Ningaloo. The new method would be weighted to the direction of prevailing and dominant wind directions but consider more than a single line that may be able to pass through a gap in the reef. A number of fetch calculators have been developed which would assist in developing this method. One such calculator *Fetch Effect Analysis Version 1.2.0* was developed by Ross Pickard and has the ability to calculate fetch lengths in 1 degree intervals with the option of summing the results. Therefore fetch lengths could be calculated every degree over 23 degrees that encompasses the south west direction and summed to get an overall value.

Gradient

The gradient of shore platforms is believed to be driven by mean water surface fluctuation and the degree in which wave erosion processes have an effect in the vertical plane (Trenhaile, 1987; 1997; 1999; 2000). Steeper platforms are associated with larger spring tidal levels (refer to Figure 33) (Trenhaile, 2000). Although the spring tidal level throughout Ningaloo was consistent, it was predicted that the extent of offshore reef and the distance to that offshore reef (orthogonal fetch) would have an impact on water levels and result in differences in gradient. This was not the case.

There is no correlation between sites with steeper gradients and the extent of offshore reef (Figure 20). This confirms work by Trenhaile (2000) who suggests that shore platforms in Australia are below 1° due to the predominately micro-tidal coastline.

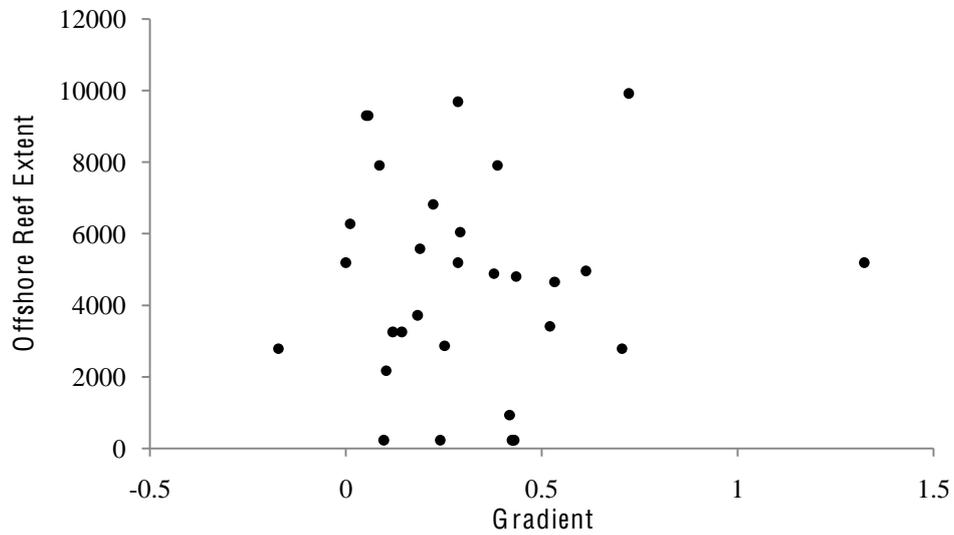


Figure 20: No correlation between extent of offshore reef and the gradient of the platform.

4. Linkages between Platform Morphotypes and Invertebrate Assemblages

Introduction

The ecology of the intertidal is well explored due to its easily accessible landscape and complex relationships between physical and biological variables. The following account will consider how the physical variables that influence morphology of platforms also influence the abundance of invertebrate species living on the platform.

Sandiness

Sediment affects intertidal invertebrate assemblages in a number of ways but its exact role in community structure can be difficult to determine (Schiel et al., 2006). Sediment presence and grain size has adverse effects on all benthic organisms (Abelson & Denny, 1997). Suspended sediment has detrimental effects on algae and corals by limiting light penetration through the water column, by covering photosynthetic surfaces (Babcock & Davies, 1991; Airoidi, 1998), completely burying individuals (Rogers, 1983; Babcock & Davies, 1991) and causing the expulsion of zooxanthellae (Rogers, 1983). Fine sediments can have an effect on the recruitment of invertebrates (particularly corals) as they are unable to settle, choose not to settle or suffer early mortality as result of settling (Aller & Dodge, 1974; Sammarco, 1980; Cortes & Risk, 1985; Wallace, 1985). Coarser sediment such as sand and gravel may scour surfaces of organisms and graze tissue or even disengage them from a solid base and wash them away. In contrast, some species have a tolerance to sand and can dominate (Littler et al., 1983).

Elevation

Organisms are affected by changing water levels due to the potential for desiccation and adverse thermal effects. Intertidal ecologists accept that desiccation is one of the major environmental factors determining the distribution limits of intertidal organisms (Connell, 1972, Lowell, 1984). Physical factors that determine the emersion time of an organism include the height of the platform relative to mean sea level, the tidal range, hydrodynamic forces leading to water setup or setdown and the topography of the substrate and its ability to retain water. Species' tolerance to the effects of emersion has resulted in the distribution of invertebrates throughout the intertidal zone. Species more tolerant to the impacts of emersion are found higher in the profile as competition is less, while competitive species less tolerant to emersion are found lower in the profile.

Wave Exposure

The impact of waves on intertidal invertebrate assemblages is far reaching. Sheltered rocky intertidal communities typically have less biomass than exposed areas (Menge & Sutherland, 1976). High energy assemblages generally have smaller gastropods (Denny et al., 1985; Paine, 1976) due to the

high mortality rates from being dislodged. Wave energy also appears to reduce mollusc feeding times (Menge, 1978) and the resultant morphology of animals including shell size.

Wave exposure can result in the following damaging effects on the invertebrates of a platform (Jones & Demetropoulos, 1968), including the abrasion from the suspension of particles resulting in damage to tissue and even death, hydrostatic pressures exerted by waves generate general compression on animals and drag as a frictional force can dislodge and remove animals, damaging them in suspension and transporting them to areas outside their fundamental niche.

Complexity

The availability of spatial refuges such as crevices determines the level of mortality from physical stress (Garrity, 1984) and the existence of some species (Menge & Lubchenco; 1981, Beck, 2000). Menge and Lubchenco (1981) found that the complexity of a surface (also referred to as spatial heterogeneity, rugosity or surface topography) plays more of a role in tropical communities such as those present at Ningaloo, compared with temperate communities. This was contrary to Bergeron and Bourget (1986), who summarised that the availability and type of spatial refuges provided by substratum irregularities were important in determining the distribution, abundance and persistence of sessile invertebrates.

Methods

Invertebrate Sampling

Invertebrate assemblages were sampled during two field trips in 2009; July (northern sites) and September (southern sites). Sampling was primarily conducted by Robert Black, Mike Johnson, Jane Prince and Anne Brearley (herein after referred to as the *WAMSI team*) with assistance from the author. The WAMSI team recorded the abundance of all macro invertebrate species in 20, 1m² quadrats, haphazardly distributed throughout the 15 metres crossshore by 50 metres alongshore sampling area. Hermit crabs were recorded as presence/absence due the difficulty in identifying them to species, their high abundance and difficulty in determining if shells had live hermits within. Further details on invertebrate sampling are in Appendix 2 – Detailed methods.

Statistical Analyses

Once all data had been entered into Microsoft Excel the total number of individuals and species was calculated for each site and the entire study area. A mean and standard error of the total number of individuals and species was calculated for each morphotype. All data were imported into the statistical analysis package PRIMER-E Primer 6 Version 6.1.11 (herein after referred to as *Primer*) as abundance data; the samples were transformed using fourth root transformation. A Bray-Curtis similarity matrix was computed correlating each site to every other site according to the occurrence and abundance of each species.

The similarity matrix was then used to conduct a Principles Coordinates Analysis (PCO) with the first two axes in the plot used to show the relationships among the sites. The PCO is calculated in the manner of Gower (1966) and is equivalent to metric multidimensional scaling (MDS) (Anderson et al., 2008). Sites with similar species assemblages will be in close proximity, while sites with dissimilar assemblages will be further apart. Sites could be identified by the morphotype to which they belong, further identifying any spatial arrangement between morphotypes.

A SIMPER analysis was undertaken to identify the species contributing to the resemblances between sites. The SIMPER analysis was conducted in Primer using fourth root transformed invertebrate abundance data with morphotype as a factor and a Bray-Curtis measure of similarity.

A Canonical Analysis of Principal coordinates (CAP) was undertaken in Primer. The CAP can be based on any symmetric distance matrix and considers two matrices, one response variable matrix (Y -biological data) and one which is of interest for a multivariate hypothesis (X - platform morphotype as a factor) (Anderson, 2004). The purpose of the CAP is to consider the effect of X on Y , if any, on the basis of distance (Anderson, 2004). CAP is different from Permutational Multivariate Analysis Of Variance (PERMANOVA) as it takes into account the correlation among the variables (Anderson, 2004). The CAP was undertaken with all fourth root transformed data with morphotype as a factor. The CAP was conducted with a permutation test (4999 permutations) and with an undefined number of axes to be determined by the analysis. When interpreting the results of this analysis one should consider the spatial relationships of samples in the output plot, the variables that are determining the spatial arrangement, the results of the permutation test using the two different test statistics (trace and largest root) and the “leave-one-out” classification of individual observations.

A Mantel test was carried out in the statistical program *R-statistic* using the package *Vegan* to determine any correlation between the Gower dissimilarity matrix used to determine platform morphotypes and the Bray-Curtis invertebrate abundance dissimilarity matrix. The Bray-Curtis dissimilarity matrix based on invertebrate abundance data was produced in the statistical program R using the package *Vegan* and used fourth root transformed abundance species data.

A univariate using PERMANOVA was undertaken for key animals to investigate if their abundance differed among morphotypes. A Bray-Curtis similarity matrix was produced using summed abundance of each species considered a key animal (i.e. the abundance of all *Cypraea* spp. were summed per site) and the MANOVA used 4999 permutations testing for difference in the factor morphotype. In some instances a pairwise analysis was also conducted with morphotype as a factor. Summary tables and column graphs of the abundance of each key animal per site and within each morphotype were produced in Microsoft Excel to further investigate any differences.

Results

Summary of Invertebrate Assemblages

A total of 184 species and 13997 individuals were recorded for all 32 sites sampled in July and September of 2009. The number of species per sites ranged from 8 at 3 Mile Out 2 to 38 at 3 Mile In 3 with an mean and standard error of 22.1 ± 1.3 . The number of individuals for each site ranged from 58 at Surfers North to 1369 at Coral Bay South with an mean and standard error 437.4 ± 60.4 .

The number of species did not statistically differ among morphotypes (Table 13) and ranged from 18 for morphotype 3 to 25.9 for morphotype 2 (Table 14). The number of individuals was statistically different among morphotypes (Table 15) and ranged from 227.9 at morphotype 1 to 1229.5 at morphotype 3 (Table 14).

Table 13: Univariate PERMANOVA summary for number of species per morphotype.

Source of Variation	df	SS	MS	Pseudo F	P(perm)	Unique perms
Between Morphotypes	4	1197.8	299.46	1.0499	0.3898	4985
Within Morphotypes	27	7701.2	285.23			
Total	31	889.1				

Table 14: Mean and standard error for the number of species and individuals for each morphotype.

Morphotype	No. of sites	Number of species		Number of individuals	
		Mean per site	Standard error	Mean per site	Standard error
1	12	21.5	1.6	227.9	38.2
2	8	25.9	2.7	374.5	69.4
3	2	18.0	4.0	1229.5	139.5
4	6	19.0	3.9	446.5	162.6
5	4	23.3	4.4	782	58.4

Table 15: Univariate PERMANOVA summary for number of individuals per morphotype.

Source of Variation	df	SS	MS	Pseudo F	P(perm)	Unique perms
Between Morphotypes	4	14426	3606.5	5.565	0.0008	4989
Within Morphotypes	27	17498	648.06			
Total	31	31924				

Principal Coordinates Analysis

Figure 21 is a plot of the PCO results conducted using all biological data with sites identified by morphotype. Although some morphotype groups overlap it is evident that there is some relationship between platform morphotype and the invertebrate assemblage found on that platform. Most sites in morphotype 4 and 5 are isolated from the all other morphotypes but sites within these two morphotypes are quite dispersed indicating some difference among them. Morphotype 3 consists of only two sites that are close to one another but are located in the middle of the other four morphotype clusters indicating no strongly defining features. Morphotype 1 which contains the greatest number of sites is, with the exception of a few sites, tightly grouped when compared to morphotype 4 and 5

indicating similarity. Sites with morphotype 2 vary according to the y-axis but are grouped strongly on the x-axis.

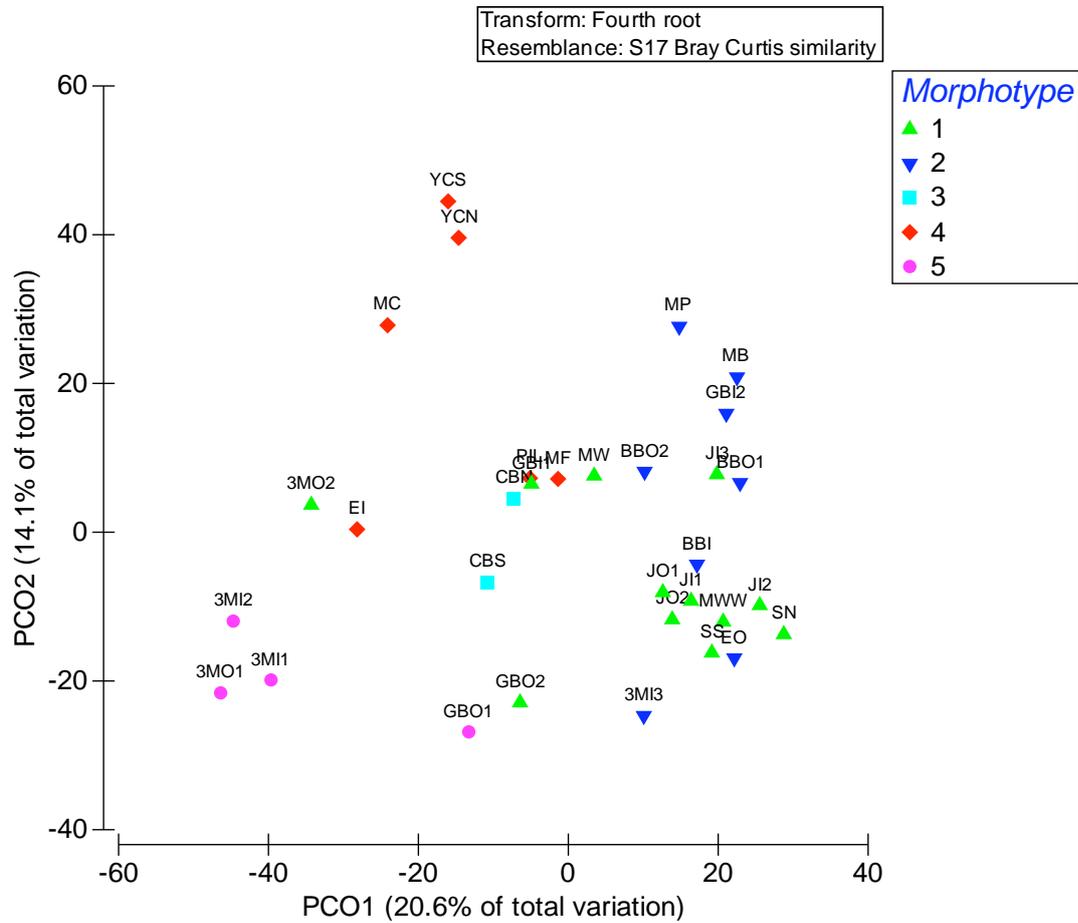


Figure 21: PCO plot using all fourth root transformed biological data.

SIMPER Analysis

The SIMPER analysis identified the mean similarity value within a morphotype and the average dissimilarity between morphotypes. Dissimilarity values within and between morphotypes, the top three species defining the similarities in invertebrate assemblages within a morphotype and the top three species defining the dissimilarities between morphotypes are displayed in Table 16.

The SIMPER analysis illustrates that the some sites within a morphotype have the same level of dissimilarity as sites of different morphotypes. For example sites within morphotype 4 have a dissimilarity of 71.36%, higher than the dissimilarity between sites of morphotypes 1/2, 1/3 and 2/3. This suggests considerable differences in the invertebrate assemblage of sites within morphotype 4.

Table 16: Mean dissimilarity values with and between morphotypes are displayed in bold. Species listed within a morphotype are the top three species causing the greatest similarity between sites within a morphotype. Species listed between morphotypes are the top three species causing the greatest dissimilarities of sites between morphotypes.

		Morphotype				
		1	2	3	4	5
Morphotype	1	53.85% <i>Serpulorbis siphon</i> cf. Hermits <i>Septifer bilocularis</i>				
	2	61.93% <i>Conus sponsalis</i> <i>Septifer bilocularis</i> <i>Strombus mutabilis</i>	58.52% <i>Strombus mutabilis</i> <i>Cronia avellana</i> Hermits			
	3	66.31% <i>Brachidontes ustulatus</i> <i>Conus sponsalis</i> <i>Strombus mutabilis</i>	70.49% <i>Brachidontes ustulatus</i> <i>Strombus mutabilis</i> <i>Cronia avellana</i>	40.04% <i>Brachidontes ustulatus</i> <i>Serpulorbis siphon</i> cf. <i>Septifer bilocularis</i>		
	4	71.56% <i>Conus sponsalis</i> <i>Strombus mutabilis</i> Coral 2mm brown	76.38% <i>Strombus mutabilis</i> <i>Cronia avellana</i> Coral 2mm brown	72.29% <i>Brachidontes ustulatus</i> <i>Acropora</i> <i>Glypeomorus batillariaeformis</i>	71.36% <i>Serpulorbis siphon</i> cf. Hermits <i>Petalconchus</i> cf.	
	5	73.79% <i>Siphonaria</i> sp. (Sept. 09) <i>Strombus mutabilis</i> <i>Thais orbita</i>	80.14% <i>Siphonaria</i> sp. (Sept. 09) <i>Strombus mutabilis</i> <i>Septifer bilocularis</i>	73.82% <i>Brachidontes ustulatus</i> <i>Siphonaria</i> sp. (Sept. 09) <i>Thais orbita</i>	79.42% <i>Siphonaria</i> sp. (Sept. 09) <i>Septifer bilocularis</i> <i>Thais orbita</i>	45.53% <i>Siphonaria</i> sp. (Sept. 09) <i>Septifer bilocularis</i> <i>Thais orbita</i>

Invertebrates Assemblages Considering Platform Morphology

Canonical Analysis of Principal Coordinates

The results of the CAP plot using morphotype as a factor are presented in Figure 22. This plot shows segregation of sites with morphotype 2, 3 and 5. Site with morphotype 1 and 4 are overlapping which suggest that they have a similar invertebrate assemblage. The permutation test results undertaken in the CAP using morphotype as a factor indicate a significant separation between morphotypes (Table 17). Table 18 summarises the results of the leave-out-allocation and indicates that majority of sites were classified in the correct morphotype (total correct: 26/32 81.25% misclassification error: 18.75%). The individual samples that were misclassified are outlined in Table 19.

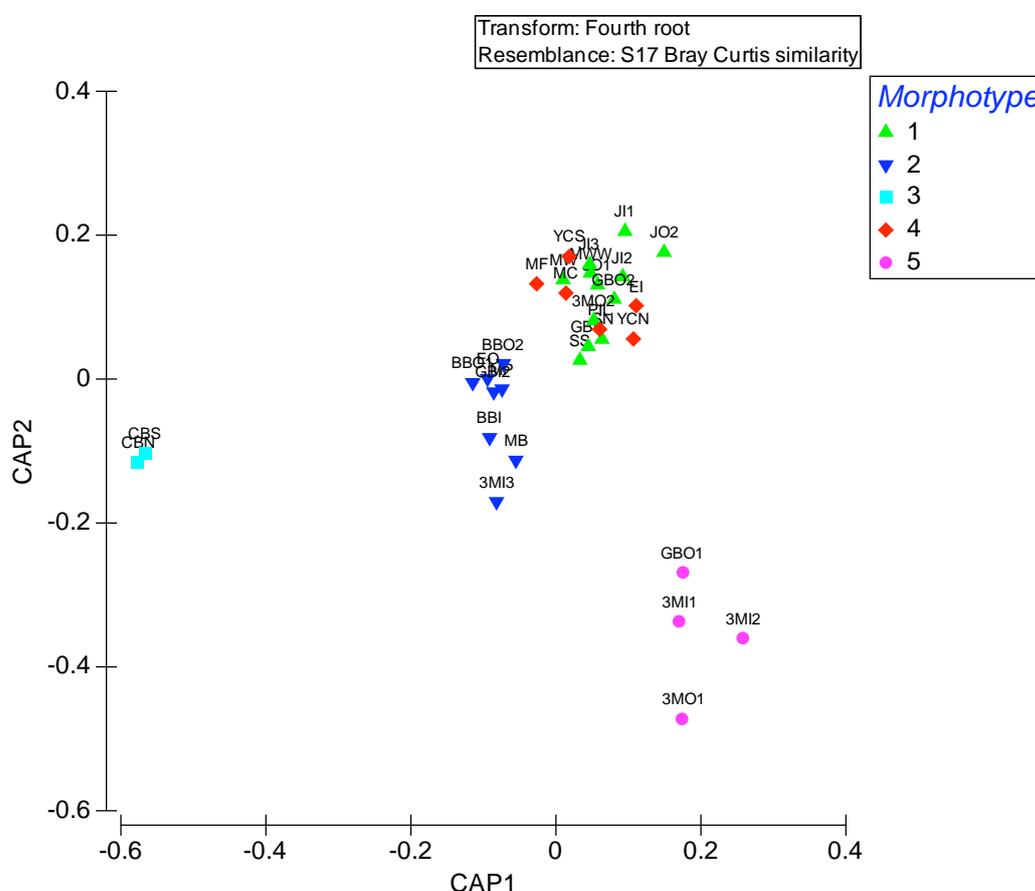


Figure 22: CAP plot produced in Primer using fourth root transformed data with Morphotype as a factor and with an undefined number of axes.

Table 17: Results of the permutation tests of the CAP undertaken in Primer with platform morphotype as a factor.

Test	Value	P-value	No. of Perms.
Trace statistic	3.39835	0.0002	4999
First squared canonical correlation (δ^2)	0.96139	0.0002	4999

Table 18: Leave-out-allocation of sites from their original morphotype to the morphotype of best fit.

Original Morphotype	New Morphotype					Total	% correct
	1	2	4	3	5		
1	9	2	1	0		12	75
2	1	7	0	0	0	8	87.5
4	1	0	5	0	0	6	83.33
3	0	0	0	2	0	2	100
5	0	1	0	0	3	4	75

Table 19: Sites that were deemed to be misclassified and their suggested new morphotype based on the biological data.

Sample	Original morphotype	New morphotype
GBO2	1	2
GBI1	1	2
3MO2	1	4
3MI3	2	1
EI	4	1
GBO1	5	2

Mantel Test

Results of the Mantel test showed statistically significant correlation between the dissimilarity of sites based on physical variables and the dissimilarity of sites based on data of abundance of invertebrates (Table 20). This indicates that the differences seen in the biological data are also correlated with the differences seen in the physical data used to classify platform morphotypes.

Table 20: Mantel test results using the same *Essential* dataset that was used to determine platform morphotypes

Platform variable dataset	r	P-value	99 th percentile	No. perms
<i>Essential</i>	0.3339	0.0001	0.200	9999

Key Animals

A number of “key species” (as well as families and genera) were investigated in detail and their abundance compared among sites and morphotypes. Key species include *Cypraea* spp. (coweries) are targeted for their shiny and patterned coloured shells that are highly prized by amateur and professional shell collectors, *Tridacna* sp. (giant clams) are collected for their meat and shells, corals (hard and soft) are seen as aesthetic organisms that the public enjoy seeing, *Conus* spp. (cones) are targeted by recreational and professional shell collectors for their highly patterned sometimes shiny shell and octopus targeted by recreational fishers for bait. As well as these identified key animals, many others exist but are in such low abundance their true distribution cannot be identified.

Cypraea spp.

The total number of *Cypraea* spp. individuals did not significantly differ between morphotypes (Table 21) but the number of *Cypraea* spp. found were particularly less abundant in morphotype 4 (Table 22). Figure 23 and Figure 24 graph the number of species of *Cypraea* spp. and number of *Cypraea* spp. individuals respectively and illustrate that a relatively high number of species does not

necessarily relate to high numbers of individuals. For example, Mangrove Bay had 4 species of *Cypraea* spp. but only 7 individuals compared with Gnaraloo Bay In 1 that had 2 species with 38 individuals.

Table 21: Results of single permutational MANOVA comparing the number of individual *Cypraea* spp. within each of the platform morphotypes.

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Morphotype	4	10152	2537.9	1.7419	0.1238	4980
Residual	27	39337	1456.9			
Total	31	49489				

Table 22: Mean and standard error for the number of *Cypraea* spp. individuals and species.

Morphotype	Number of species		Number of individuals	
	Mean per site	Standard error	Mean per site	Standard error
1	0.8	0.3	5.8	3.4
2	1.5	0.5	5.8	1.7
3	1.0	0.0	4.5	3.5
4	0.7	0.3	0.8	0.5
5	0.8	0.3	5.5	3.1

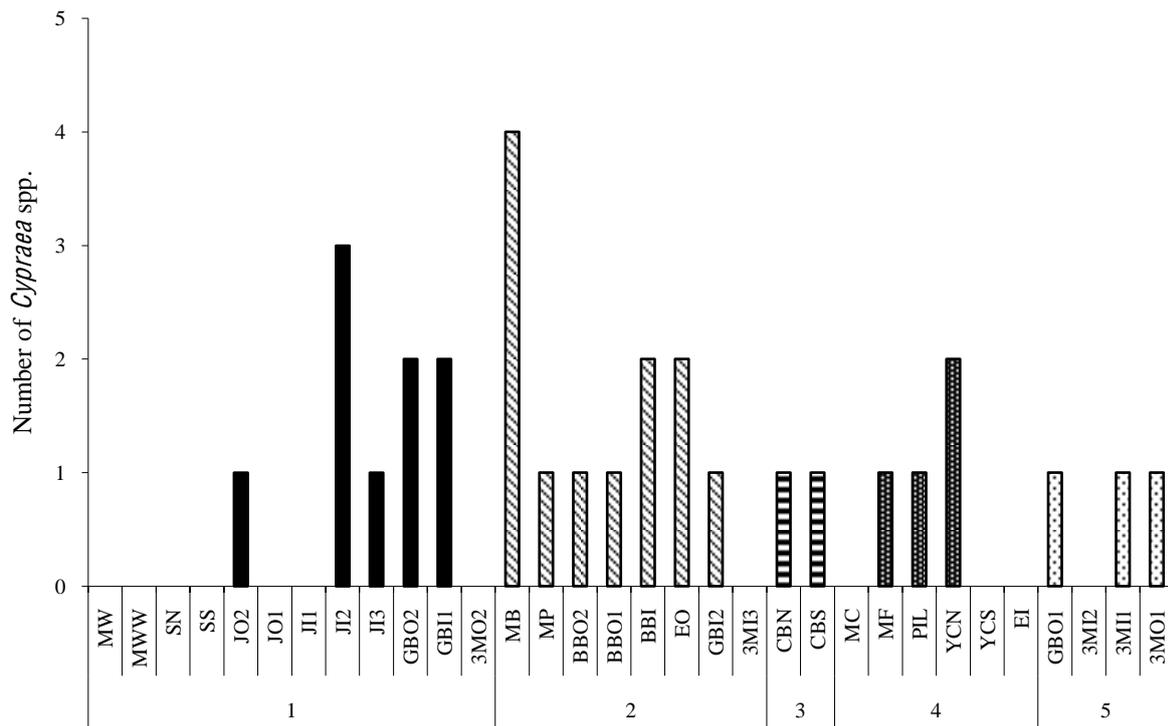


Figure 23: Number of *Cypraea* spp. species found for each site within each morphotype.

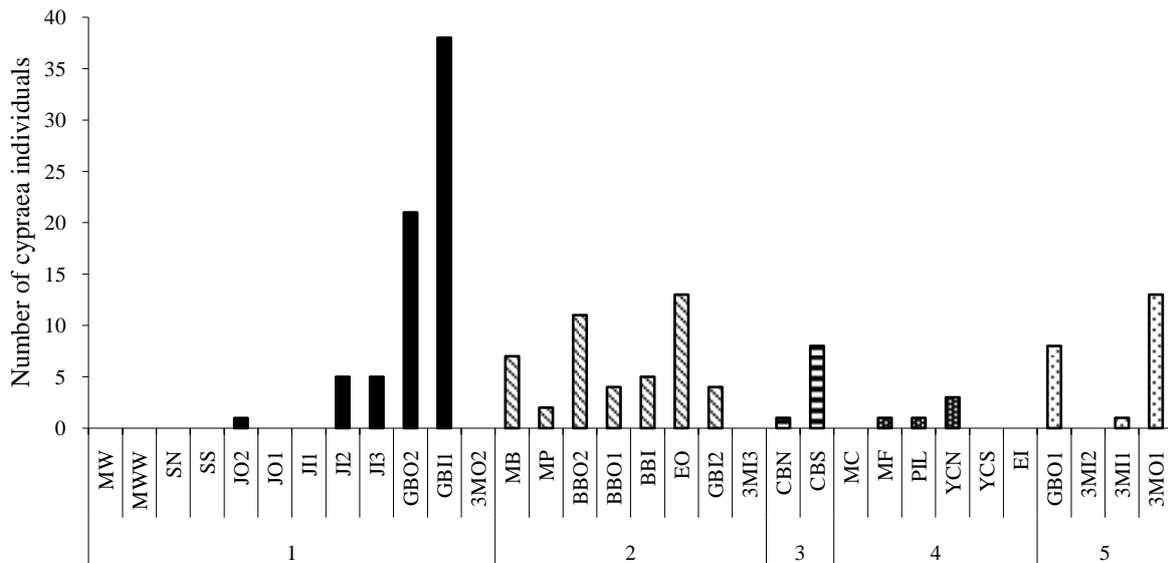


Figure 24: Total number of individual *Cypraea* spp. found for each site within each morphotype.

Tridacna spp.

The number of *Tridacna* spp. does not significantly differ among morphotypes (Table 23) even though it is evident from Figure 25 that Elle’s Out and 3 Mile In 3 which have morphotype 2 have considerably more individuals than all other sites (Figure 25). However, when the number of individual *Tridacna* spp. were tested in a pairwise comparison of morphotypes, morphotype 2 was statistically different from morphotype 1 and 4.

Table 23: Results of univariate PERMANOVA comparing the total number of individual *Tridacna* spp. within each of the platform morphotypes.

Source	df	SS	MS	Pseudo-F	P(perm)	Perms
Morphotype	4	10152	2537.9	1.7419	0.1144	4982
Residual	27	39337	1456.9			
Total	31	49489				

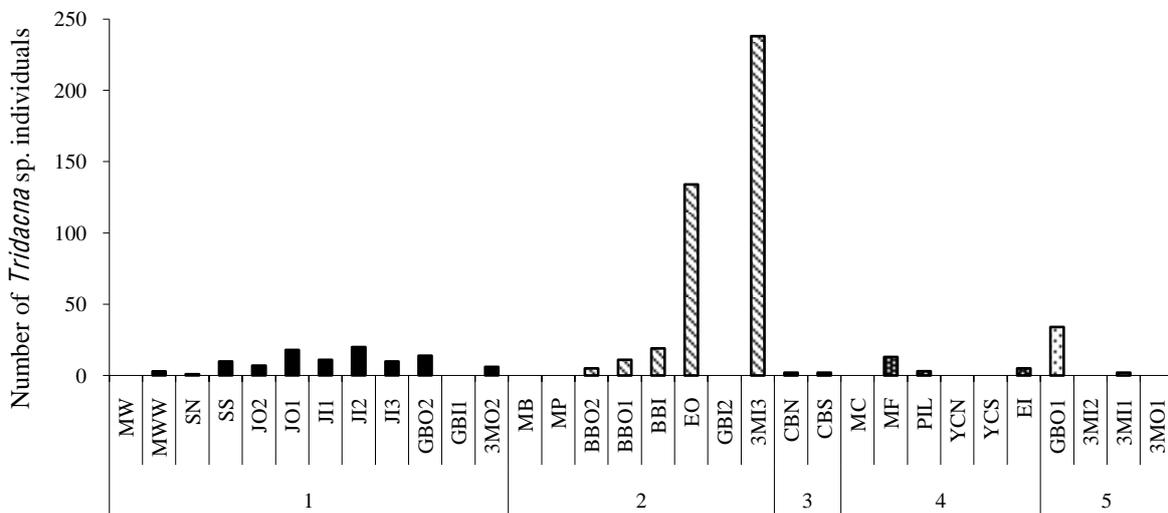


Figure 25: Number of individual *Tridacna* spp. found at each site within each morphotype.

Table 24: Pairwise comparison results of a single permutational MANOVA between morphotypes using the number of individual *Tridacna* spp. per site.

Morphotype	t	P(perm)	perms
1, 2	1.9712	0.0392	1009
1, 3	0.86326	0.5476	18
1, 4	0.90719	0.437	84
1, 5	0.83429	0.4536	89
2, 3	0.3816	0.912	37
2, 4	2.6864	0.0158	443
2, 5	0.67797	0.6122	213
3, 4	1.4321	0.2498	8
3, 5	0.2865	1	8
4, 5	1.4464	0.17	27

Corals

The number of individual heads of coral was statistically different among morphotypes (Table 25). Figure 26 shows that a number of coral species occur at all platform morphotypes but are consistently abundant in morphotypes 1, 2, and 3. Figure 27 further illustrates the abundance of individual coral heads at morphotype 1, 2 and 3. Furthermore the mean number of species and individual coral heads is greatest at morphotype 2 (3.3 and 18.6 respectively), followed closely by morphotype 3 and 1 (Table 26). Morphotypes 3 and 4 have very low numbers of species and individual coral heads.

Table 25: Results of univariate PER MANOVA comparing the number of individual coral heads within each of the platform morphotypes.

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Morphotype	4	23831	5957.6	3.9242	0.0026	4987
Residual	27	40991	1518.2			
Total	31	64822				

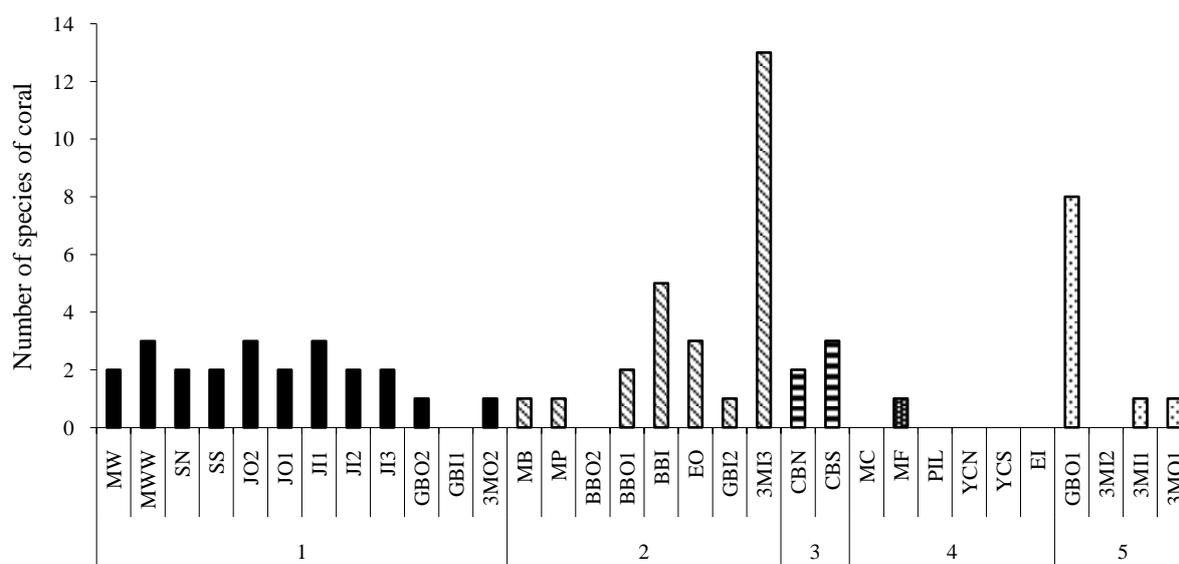


Figure 26: Total number of species of corals per site within each morphotype.

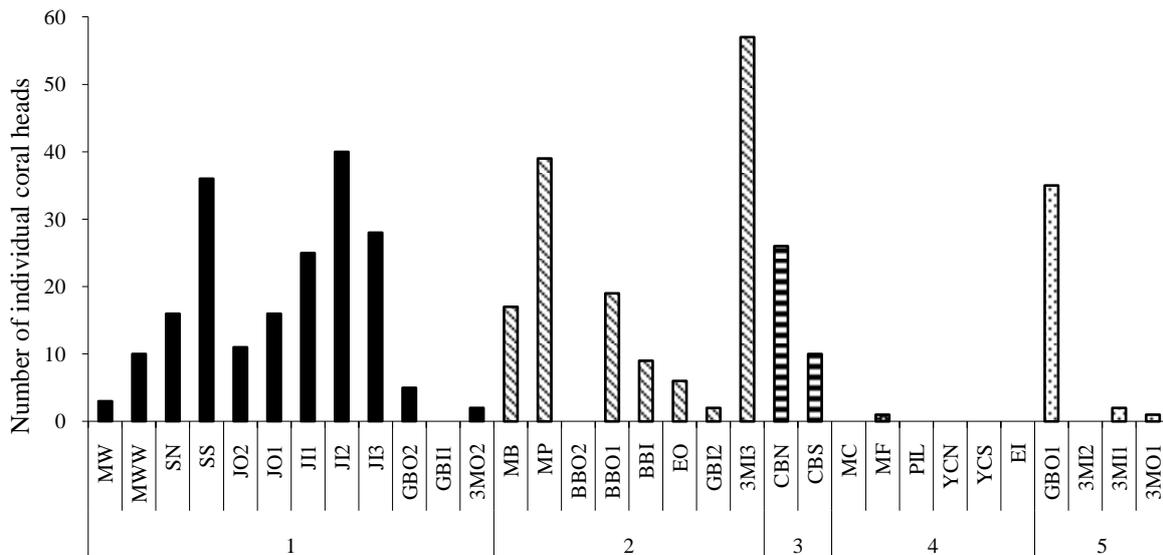


Figure 27: The total number of heads of coral per site within each morphotype.

Table 26: Mean and standard error for the number of individual coral heads and species.

Morphotype	Number of species		Number of coral heads	
	Mean	Standard Error	Mean	Standard Error
1	1.9	0.3	16.0	3.9
2	3.3	1.5	18.6	7.0
3	2.5	0.5	18.0	8.0
4	0.2	0.2	0.2	0.2
5	2.5	1.8	9.5	8.5

Conus spp.

Conus spp., more commonly known as cone shells are abundant on many of the shore platforms at Ningaloo. Their abundance among morphotypes is statistically different (Table 27) with the greatest number of individuals occurring at morphotype 1 and 2 (Figure 28). Figure 29 illustrates that morphotypes 1 and 2 also have the greatest number of species of *Conus* spp. per site compared to the other morphotypes. Further investigation of cones numbers revealed that *Conus sponsalis* was the most abundant *Conus* spp. and primarily found at morphotypes 1 and 2 (Table 28).

Table 27: Results of univariate PERMANOVA comparing the number of individual *Conus* spp. within each of the platform morphotypes.

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Morphotype	4	15442	3860.5	2.8536	0.0156	4982
Residual	27	36527	1352.9			
Total	31	51969				

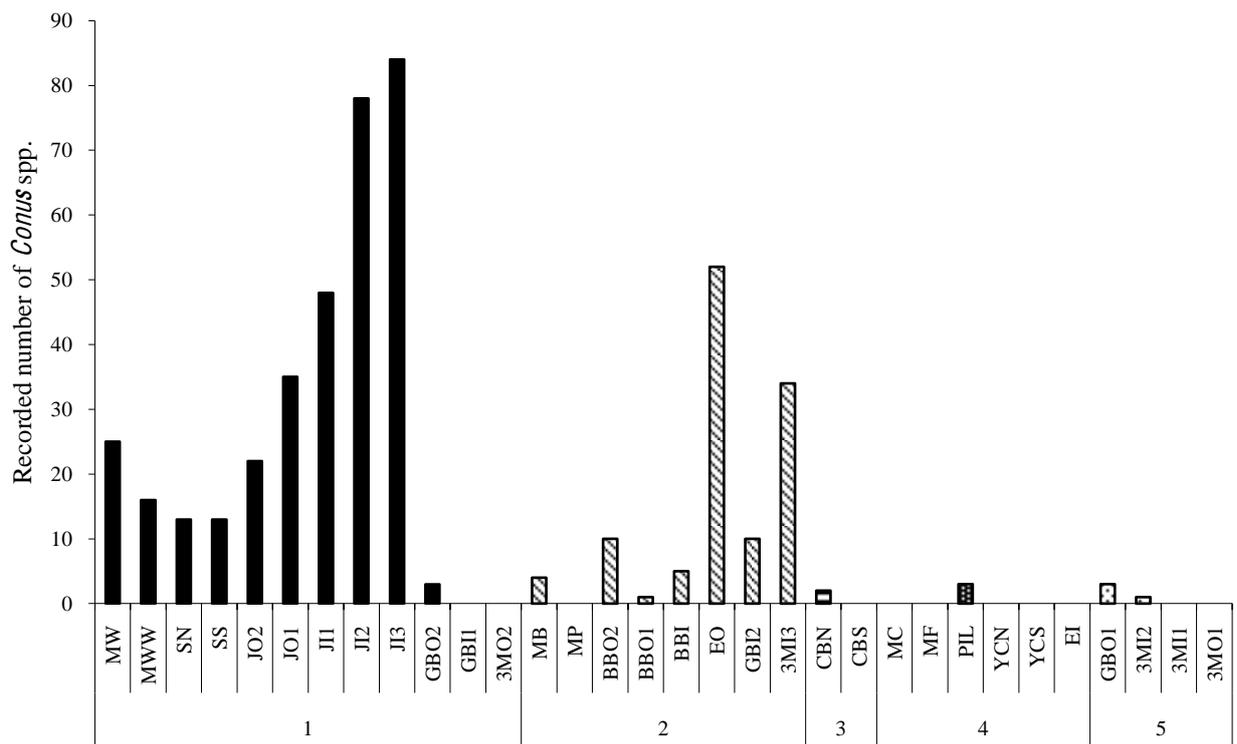


Figure 28: Total number of individual *Conus* spp. per site within each morphotype.

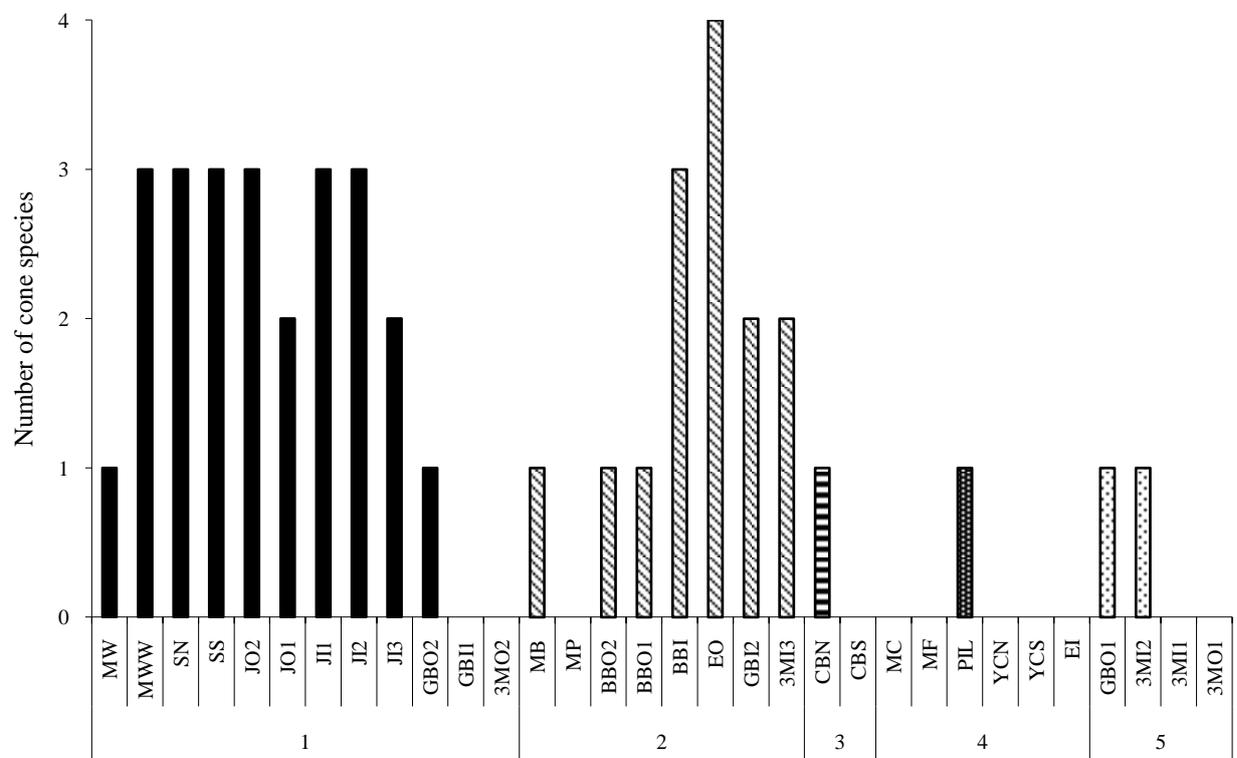


Figure 29: Total number of *Conus* spp. species per site within each morphotype.

Table 28: Abundance of all recorded *Conus* spp. species at each morphotype and in total throughout entire study site..

Morphotype	<i>C. chaldaeus</i>	<i>C. corticus</i>	<i>C. dorreensis</i>	<i>C. ebraeus</i>	<i>C. lividis</i>	<i>C. sponsalis</i>
1	0	0	19	0	11	307
2	1	1	34	1	4	75
3	0	0	2	0	0	0
4	0	0	0	0	0	3
5	0	0	1	0	0	3
Total	1	1	56	1	15	388

Octopus

Although many octopuses were seen throughout the study area during sampling, none were recorded in the quadrats.

Discussion

These results suggest that forcings determining platform morphology have some determination on the invertebrate assemblages. Results of the CAP and Mantel test indicate that understanding platform morphology can help to explain differences in invertebrate assemblage. Linkages between morphology and invertebrate assemblages could be due to regional differences in broad scale geology and processes. Closer examination of linkages between platform morphology and species abundance identified relationships. Key variables affecting the abundance of invertebrate species include complexity, the presence of a sand veneer, the level of wave exposure and the height of the platform surface will be discussed below. A final summary of the invertebrate assemblages per morphotype, considering key animals and those identified from the SIMPER analysis is described in Table 29.

Table 29: Summary of linkages between platform morphology and a number of key animals including the top three species identified from the SIMPER analysis.

Morphotype	Morphotype description	Invertebrate assemblage description
1	A low platform that has medium complexity values. The platform has a grading edge with an extensive low tide terrace resulting in low exposure at low tide. Little to no offshore reef results in medium to high exposure at high tide. Sites have a ramp and a sand veneer	Animals from the genus <i>Conus</i> spp. are abundant particularly <i>Conus sponsalis</i> and <i>Conus lividis</i> likely due to the amount of sediment present. Corals species and the number of individuals are relatively high likely due to the protected platforms and location in the northern half of the study area. <i>Tridacna</i> spp. are consistently present throughout most sites but not in high abundance. <i>Cypraea</i> spp. are found in half the sites when present in great abundance. The top three species most likely to be found at all sites include <i>Serpulorbis siphon</i> cf., Hermits and <i>Septifer bilocularis</i> .
2	Slightly higher elevation than morphotype one with the highest fine scale complexity values. The platform has a grading edge with a ramp present at some sites. Offshore reef is extensive, providing protection from swell waves. Sites have a sand veneer that is thick and silty in at some sites.	Invertebrate assemblage is similar to morphotype 1 with a high number of coral species and individuals. This morphotype has a high number of species of <i>Conus</i> spp. but with low-medium abundance. It has the two highest abundances recorded for <i>Tridacna</i> spp. although not present in all sites like morphotype 1. <i>Cypraea</i> spp. are common but <i>Cypraea moneta</i> are consistently occurring in relatively high abundance likely due to the higher levels of silt and complex surface. The top three species most likely to be found at all sites include <i>Strombus mutabilis</i> , <i>Cronia avellana</i> and Hermits.
3	This sites is characterised by an extensive and continuous offshore reef system that attenuates swell waves. The platform edge terminates with a low tide cliff into a sandy wide lagoon where wind waves develop. These short period waves are responsible for a small ramp. The platforms are covered with a thin sandy veneer and the elevation is relatively medium. Complexity values are similar to that off morphotype 2	This morphotype was dominated by <i>Brachidontes</i> sp. and resulted in this morphotype having the greatest number of individuals than any other morphotype. Several coral species are common in abundance while <i>Tridacna</i> spp. are not. <i>Cypraea</i> spp. and <i>Conus</i> spp. both occur on these platforms but not in any high abundance. The top three species likely to be found at all sites include <i>Brachidontes ustulatus</i> , <i>Serpulorbis siphon</i> cf and <i>Septifer bilocularis</i> .
4	This platform is characterised by discontinuous offshore reef with many large gaps allowing swell wave energy to penetrate. As a result large boulders and cobbles are present on the beaches and the surface of the platform. Platform height is relatively medium to high and the complexity values indicate a flat and smooth platform surface. No ramp is present.	This assemblage has very few corals, <i>Conus</i> spp., <i>Cypraea</i> spp., and <i>Tridacna</i> spp.. It is likely to have high abundance of <i>Cronia</i> spp. The top three species likely to be found at all sites include <i>Serpulorbis siphon</i> cf., Hermits and <i>Petalococonchus</i> cf..
5	This morphotype is the best defined due to its high level of wave exposure. The platform is smooth and narrow with some deep rock pools. The seaward edge of the platform terminates into a low tide cliff with surging wave and the shoreward edge is defined in most cases by a high notch. This is the only morphotype without a sediment layer due to its high energy. It is the highest of all the morphotypes.	Similarly to its morphology, the invertebrate assemblage of this morphotype is well defined. Expect low number of <i>Conus</i> spp., corals, <i>Tridacna</i> spp. and <i>Cypraea</i> spp.. Expect high abundance of barnacles and other animals that like high wave energy. The top three species likely to be found at all sites include <i>Siphonaria</i> sp. (Sept. 09), <i>Septifer bilocularis</i> and <i>Thais orbita</i> .

Regional Differences

Although three of the five morphotypes have sites from both north and south of the study area, a north-south distribution of morphotypes and invertebrate assemblages is evident (Figure 30). This may be due to a number of factors, the first due to sampling design. Because sites were selected to test the impact of sanctuary zones they were nested around the sanctuary boundary and sometimes on the same length of platform. This meant that broad scale measurements such as offshore reef, width and coastal heterogeneity were very similar and therefore spatially close sites were more likely to be clustered together. Similarly, spatially close sites did not considerably differ in habitat type or morphology therefore the invertebrate assemblage present was similar.

Secondly, latitudinal differences in processes not measured in this project could explain regional variation in invertebrate assemblages (Sagarin et al., 1999; Southward et al., 2000; Connolly et al., 2001). Such processes include currents and sea temperature that can determine the geographical distribution of certain species (Sagarin et al., 1999; Southward et al., 2000; Connolly et al., 2001). Species distribution also affects geomorphology (see Butler, 1995). For example, it is hypothesised that the northern sites have a greater variety of corals and hence a more complete offshore reef that limits the amount of swell energy the coastline receives in turn controlling morphology.

Finally, geology is suspected to be a major variable in controlling morphology and thus invertebrate assemblages at Ningaloo. Geology was assumed constant throughout the study area but field observations suggest otherwise. As described, geology is one of the major factors in platform morphology (Sunamura, 1992; Thornton & Stephenson, 2006; Kennedy, 2009) and should be considered in any future work conducted in the area.

In consideration of these points one could question the usefulness of the morphotype classification and its relationship to invertebrate assemblages. This project has identified relationships between platform morphology and invertebrate assemblage. Although these relationships are not precisely defined by the physical variables measured, one must still consider platform morphology as a tool for predicting invertebrate assemblages. No matter what physical variables determine the abundance of particular invertebrate species this project has shown that the shore platform shape and its associated invertebrate assemblage are linked somehow.

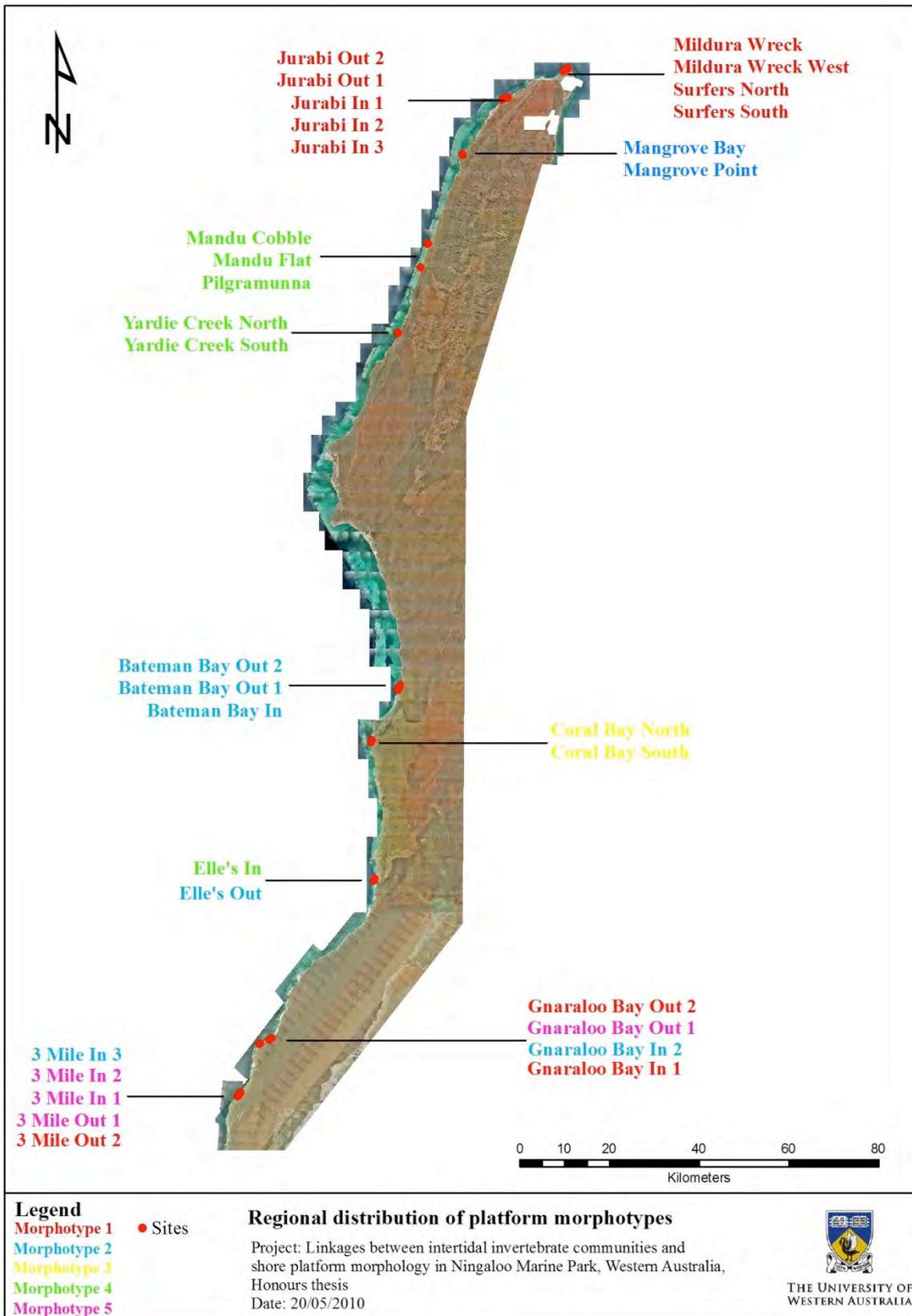


Figure 30: Distribution of morphotypes in the study area. Sites are listed from north to south.

Linkages between Platform Attributes

Wave Exposure

As described in the chapter Platform Morphology, from the results of this project it is believed that the level of wave exposure is the driving force behind the major morphological differences of the platforms investigated and controlled by the extent of offshore reef and how far that offshore reef is from the coast. Morphotype 5 had the greatest exposure to wave energy as evident from the results and from observations in the field. When the abundance of particular species is investigated, it is evident that this morphotype has a well defined invertebrate assemblage that is likely to be driven by wave exposure. One species that was identified to be causing the spatial segregation of morphotype 5 in the SIMPER analysis was *Siphonaria* sp.. The genus *Siphonaria* is better known as false limpets and commonly occurs in high energy intertidal environments (Levings & Garrity, 1994; see also Branch & Cherry, 1985). Figure 31 illustrates that *Siphonaria* sp. is found predominately in morphotype 5, occurring in high abundance in all sites. It is important to note that GMO1 in morphotype 5 is approximately 15 kilometres from the 3 Mile sites but still has a large number of *Siphonaria* sp. present.

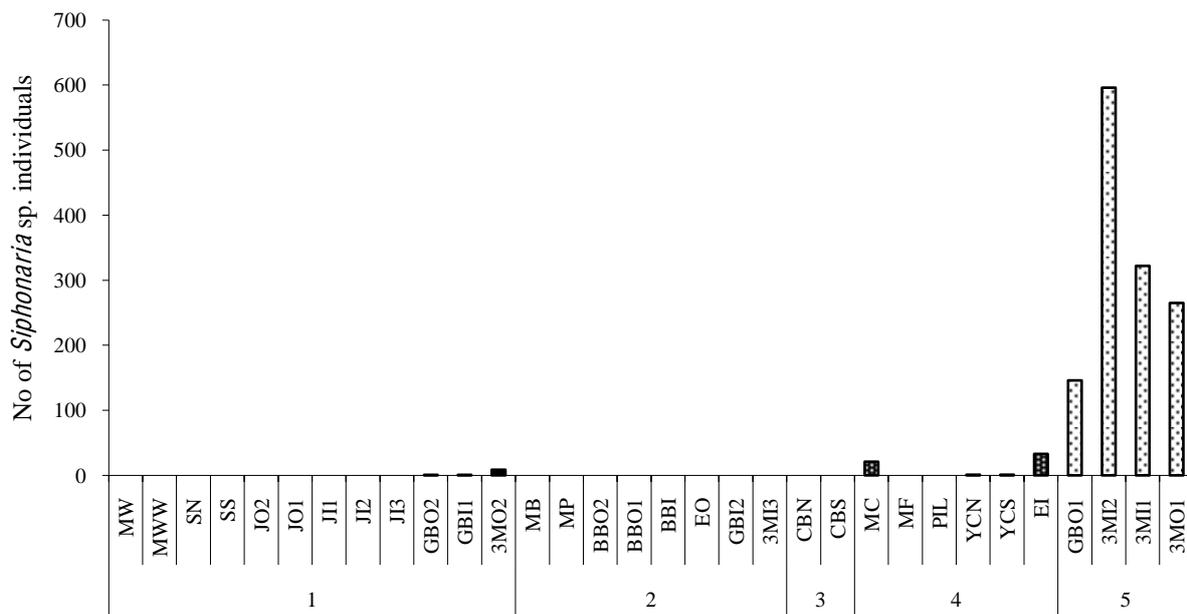


Figure 31: Number of *Siphonaria* sp. recorded at each site within each morphotype.

Another genus commonly found in higher energy environments is barnacles. Five barnacle species were recorded throughout the study area. The abundance of these five species was summed and their total abundance illustrated in Figure 32. Species that are not expected to occur in high abundance at morphotype 5 include animals from the genera *Strombus*, *Cerithiidae* and *Conus* (particularly *Conus sponsalis*) (see Appendix 7 – Invertebrate assemblage charts.)

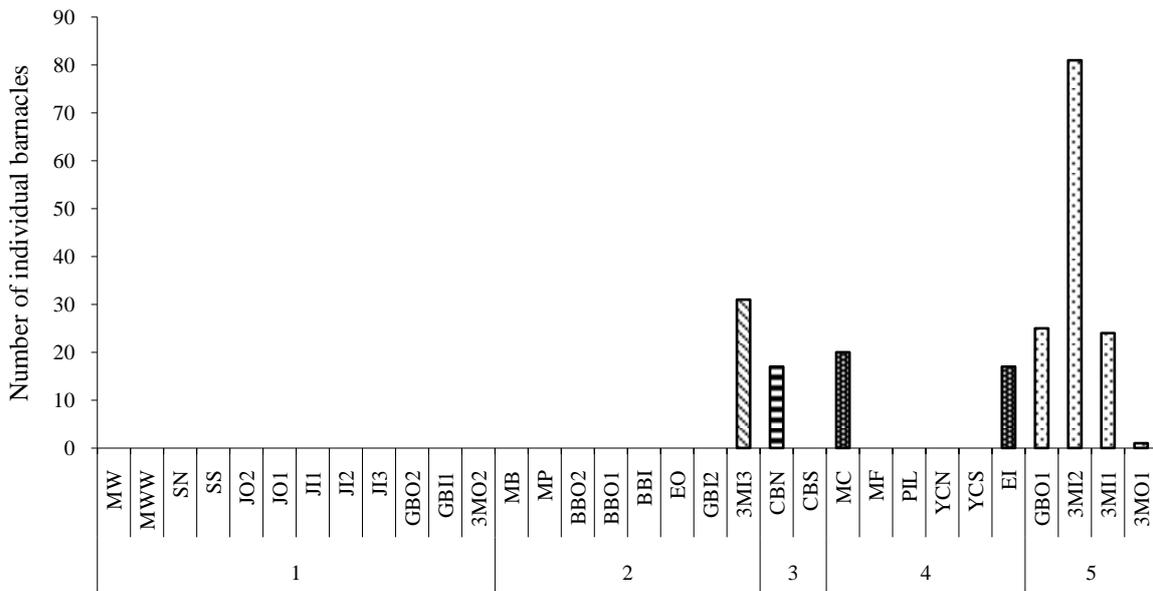


Figure 32: Total number of barnacles found at each site within each morphotype.

Sediment Veneer

The volume of sediment on a platform at any one time is variable and determined by exposure to wave energy, storminess, heavy wave action and runoff (Littler et al., 1983; Stewart, 1983; Schiel et al., 2006; Cassata & Collins, 2008). Although the amount of sediment was not measured, the presence or absence of a sand veneer was used to classify platforms. The only morphotype that did not have a sand veneer was morphotype 5. As discussed above morphotype 5 had the greatest level of wave exposure and a distinct invertebrate assemblage which may also be explained by the lack of sediment.

Despite not measuring the coverage and amount of sediment on each platform it could be inferred from the other morphological attributes. As discussed in chapter Platform Morphology, smoother platforms at the fine scale are likely to be a result of waves removing eroded or partially eroded material from the platform surface. Sites with more complex surfaces indicate eroded material such as sediment has not been removed. This collected sediment further contributes to the mechanical scour and erosion of the platform (Sunamura, 1992). Additionally, platforms with a grading edge are likely to have more sand than those with a low tide cliff as sediment can move onshore more easily (Da Silva, unpublished; Trenhaile, 2004). Two morphotypes with a grading edge, relatively high complexity, relatively low wave exposure and a sand veneer are morphotypes 1 and 2. Sites with morphotype 1 and 2 have a high number of recorded *Conus* spp. and a relatively high abundance of *Conus* spp. individuals (see Figure 28 and Figure 29 above), which could be attributed to the presence of a sediment veneer and sand patches. Kohn (1959) recorded the preferred habitats of *Conus* spp. in

Hawaii and reported most specimens (61%) occupied sandy substratum. Kohn (1959) suggested that the abundance of some species are limited by absence of sandy environments (*Conus lividus*) while others prefer reworked coral rubble (*Conus sponsalis* and *Conus imperialis*).

A potential source of sediment that this project does not consider in its final morphotype description is dune and beach. Sites have a different high water interface with varying amounts and stability of sand. At many of these sites, large volumes of sand have the potential to move offshore and onto the platform during high energy events, smothering many of the invertebrates. Sites believed to be more susceptible to smothering have a high water interface classified as beach, beach rock or pocket beach and have a grading platform. This combination of available sediment onshore and a grading platform mean that any sediment moved in the cross shore is likely to stay on the platform surface until it is slowly recovered back into the high water interface. The opposite case involves sites with a low tide cliff where sediment is likely to move offshore past the low tide cliff where it will be slowly returned over the low tide cliff and into the high water interface. Smothering events such as these have the potential to result in mass death of some species leading to species succession and an increase in the species diversity (Littler et al., 1983)

Complexity

From the results and discussion presented in the Platform Morphology section the fine scale complexity of a platform is likely to be driven by the level of wave exposure, with highly exposed sites likely to have smoother surfaces than lesser exposed sites. Several workers have identified the importance of complexity showing that the level of mortality from physical stress (Garrity, 1984) and the existence of most species seems to be entirely dependent on the availability of spatial refuges such as crevices (Menge & Lubchenco, 1981; Beck, 2000). As mentioned above, it is suggested that complexity also determines the sandiness of a site and the retention of that sand in small refuges. Medium scale complexity did differ among morphotypes but it was not believed to be having an impact on the invertebrate assemblages being recorded as rock pools were avoided in sampling.

Height

The height of the platform will determine how long an organism is likely to spend out of the water during low water periods. The higher the platform the longer it is expected to be emersed. Even though platform height at Ningaloo varies considerably between morphotypes it is believed that it is not having a major affect on the invertebrate assemblages present. This is because high level platforms such as those in morphotype 5 occur in high energy environments allowing water to be continually splashed over the low tide cliff wetting the narrow platform. This constant spray and small surge of water over the smooth platform is enough to ensure the surface does not completely dry. Some sites are an exception to this including Yardie Creek North and South which are both

relatively high and wide with grading platforms that attenuate all wave energy at low tide. Such sites are likely to be more susceptible to long periods of emersion.

Key Animals

The results presented suggest that, with the exception of *Cypraea* spp. and corals, the abundance of key animals at Ningaloo cannot be accurately predicted from the platform morphotypes identified here. This could be due to the influence of sanctuary zones but will need further investigation. Although the abundance of corals did significantly differ between morphotypes it is predicted that this difference is not primarily due to the difference in platform morphology but because the morphologies with greater coral abundance are found further north in more tropical waters. Although key species abundance cannot be accurately predicted from the morphotypes developed here, it is believed that this classification system will provide assistance in determining future locations of site specific intertidal invertebrate research.

5. Conclusion

In total, 5 morphotypes were developed from an investigation of onsite variables measured in the field and offsite variables measured using desktop methods. The final typology considered the cluster results from the Essential dataset that best represented the observed morphological differences seen between sites and the overall cluster results from the other subsets of data. Differences in morphology included the extent and continuity of offshore reef, the surface complexity of the platform, the terminus of the platform at the low water level, platform height, platform width and the presence of a sand veneer and boulders/cobbles. This project has identified that the extent of offshore reef and the amount of swell wave energy passing through gaps in this reef is the primary driver in determining the morphology of platforms at Ningaloo. There are latitudinal differences in the morphology of platforms at Ningaloo likely due to broader scale variables not considered in this project such as geology.

Intertidal invertebrate assemblages at Ningaloo are diverse with over 184 species recorded across the 32 sites. Traditionally, a single physical variable has been used to describe species abundance and with great success. However, results from this project suggest that platform morphology determined from a sweep of broad and fine scale variables can help to explain differences seen in invertebrate assemblages at Ningaloo. These morphotypes can predict the abundance of some species with confidence including *Siphonaria* spp, *Cronia avellana*, *Thais orbita*, *Conus sponsalis* and *Strombus mutabilis*. Similarly to platform morphology, latitudinal differences in invertebrate assemblages occur throughout the study area. It is unclear if these latitudinal differences are a result of differences in platform morphology or other broad scale processes not considered in this project- likely a combination of both.

The application of these results are far reaching but likely to be used by conservation managers that want to determine where specific species are most likely to occur. This typology's predictive power will allow marine managers to identify specific sites to conduct fine scale research on a particular invertebrate assemblage. This typology also adds to the limited knowledge of rocky coast geomorphology in Western Australia and could be used by coastal planners and managers as a baseline to assess how sensitive and vulnerable rocky coasts are.

Limitations and recommendations

The primary limitations of this project were time constraints and the limited knowledge of rocky coast geomorphology and processes at Ningaloo. Given more time it would be useful to experiment with the different methods used in this project to determine and further developed the most accurate. One method that needs to be refined is determining the fetch or wave exposure of each site. This could be done with site specific wave height information coupled with the development of a wave exposure index specific for Ningaloo that considers offshore reef, lagoon width and depth.

A major limitation of this investigation was the clustering of sites on the same length of continuous platform. Because sites were chosen by the WAMSI team with intent on finding the influence of sanctuary zones on invertebrate assemblages, most were clustered together around the boundary of a sanctuary zone. Therefore, the platform morphotype and the associated invertebrate assemblage are likely to be the same because they are spatially close. This is an issue for morphotype 3 and 4 which have a limited number of sites that are spatially very close to one another. In saying this, linkages between morphotype and invertebrate assemblage have been shown in other instances where sites have not been close to one another. Future research of platform morphology and its associated biology should ensure sites are far enough apart that they are not considered the same platform.

A further recommendation would be to undertake an investigation of the geology of each platform. It was assumed that the geology of the Ningaloo coastline was the same or similar enough not to be a major determinant in platform morphology. Closer examination of the platform surfaces suggested that the geology, particularly rock hardness, may differ among platforms. It is recommended that future work on platforms at Ningaloo consider the hardness of the platform through Schmidt Hammer testing, as it has been suggested that rock hardness has an influence on platform morphology (Day, 1980; Sunamura, 1992; Trenhaile et al., 1999; Thornton & Stephenson, 2006; Blanco-Chao, 2007; Kennedy, 2009).

Although invertebrate abundance data were available for most sites from previous years it was not used due to inconsistent sampling methods and changes in the assemblage and platform attributes over time. This project provides a snapshot of platform morphology and invertebrate assemblages for 2009. Further research should be continued and these results reviewed to ensure seasonal, annual and inter-annual variation in platform morphology and invertebrate assemblages are captured and considered in predictive tools.

Finally, research into the rocky coast geomorphology at Ningaloo should continue, with the primary objective to develop an inventory of all shore platforms and rocky coastline in the area. It will be from this that a refined morphological typology be developed including such things as beach type, local geology and offshore bathymetry. This research would not only assist in predicting invertebrate and other marine assemblages, it would provide the basis for a state and regional Coastal Planning Strategy vital in assessing the impacts of a changing climate.

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Appendix 1 – Extended literature review of platform height, gradient and width.

Platform Height

Elevation has been described as one of the most important morphological aspects of platforms (Sunamura, 1991, Trenhaile, 1978, Trenhaile et al., 1999). Factors affecting the height of a platform include, but are not limited to, the intensity of waves (Kirk, 1977), the strength of platform forming rocks (Gill, 1972), the weathering of rocks (Hills, 1972, Bartrum, 1916) and the tidal range (Hills, 1972, Trenhaile, 1978). However, it is difficult to determine how each factor controls platform elevation (Sunamura, 1991).

Gill (1972) summarised the height of platforms throughout the world and their erosional history from previous higher sea levels. The study concluded three main points:

1. All other things being equal, the lithology of the platform will determine the height of it;
2. Macro-tidal stormy coasts such as the U.K., the sea is the dominant driver; and
3. Hot humid environments such as Hawaii, weathering is the dominant driver.

Since then, Trenhaile (1987), Sunamura (1991), Thornton and Stephenson (2006) confirmed that mean platform height increases with rock strength. Conversely, Kennedy (2009) found no relationship between rock hardness and platform elevation and described any correlation to be completely random. In addition, Homma & Horikawa, (1965) and Sunamura (1973; 1975) suggested that platforms cut by breaking waves may be at slightly higher elevations than those produced by broken waves.

Gradient

The gradient of a platform is thought to be driven by forcings such as waves and the distribution of these forcings across the platform profile. Modelling by Trenhaile (1983), investigated the relationship between the distribution of wave energy through tidal range and the shape and gradient of a platform. Assuming that erosion rates across a platform were the same, Trenhaile concluded low gradients must be associated with high tidal duration during neap tides, while steeper but narrower sections of platform occur at the spring tidal extreme where the tidal duration is the lowest. Therefore, a platform profile should be steeper at both the LLW (low low water) and HHW (high high water) marks and vary in gradient and width with varying tidal ranges.

Trenhaile (1987, 1997, 1999, 2002) further described the relationship between platform gradient and tidal range was due to the tides controlling the elevation of the mean water surface and the degree to which wave erosion processes have an effect in the vertical plane. Spring tidal range was correlated to the gradient of the platform (Figure 33).

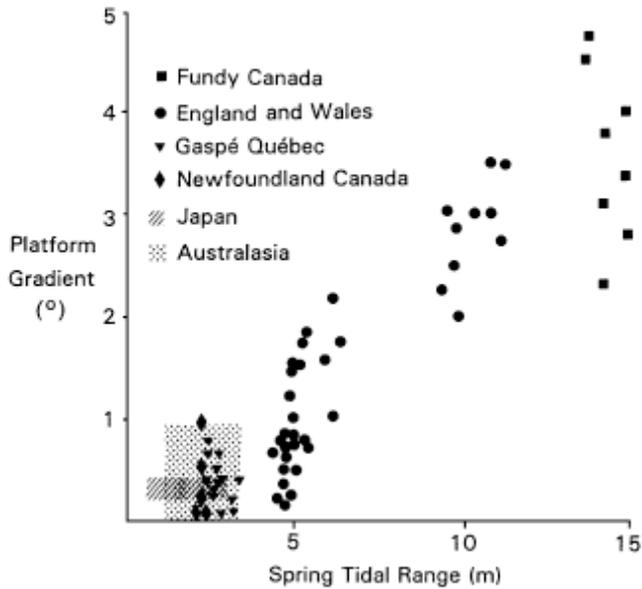


Figure 33: The relationship between shore platform gradient and the spring tidal range. Each point represents the mean of a number of profiles surveyed (Trenhaile, 2002)

Dramatic changes in platform gradient are sometimes experienced above mean sea level and are known as ramps. Ramps are a common feature on rocky coasts all over the world but their presence or absence is not fully understood. Ramps are seaward-sloping, are between the base of the cliff and the beginning of the sloping platform and can have a smooth and scoured surface (Sunamura, 1992). It has been suggested that ramps are associated with swell wave environments of low tidal range (Hills, 1949; 1971; Healy, 1968; Trenhaile & Layzell, 1981). However, in some cases the presence of an upper level ramp can be indicative of platform gradient and water levels during the last glacial and interglacial periods and inherited into the current morphology (Trenhaile, 2002) (Figure 34).

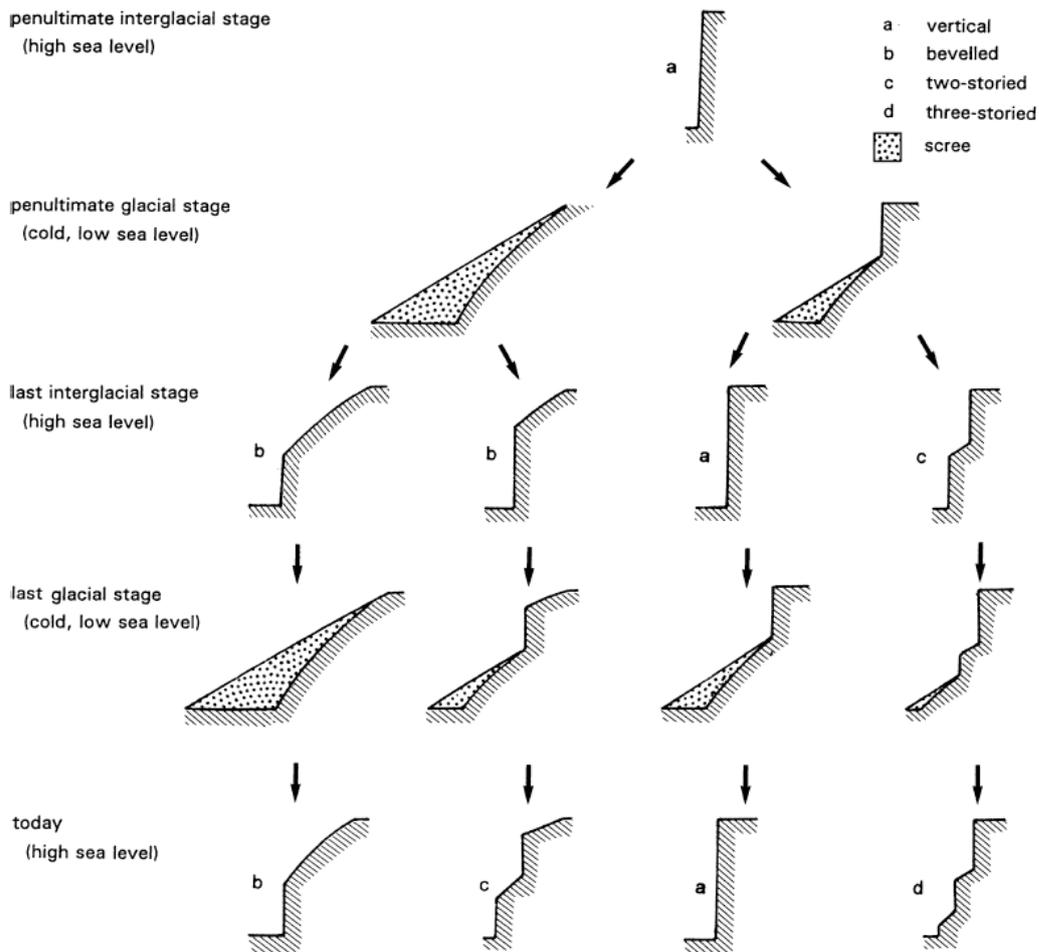


Figure 34: Simulated cliff development during past interglacial cycles on mid to high latitude coasts (Griggs & Trenhaile, 1994) from Trenhaile (2000). Development is a result of scree accumulation at the foot of the cliff and its removal during time of high water level.

Width

Platform width is one of the most important features of a shore platform (Trenhaile, 1987; Sunamura, 1992). Kennedy (2009 in press) claimed that wide platforms were associated with higher wave energy and platforms with little wave energy had narrow platforms or just consisted of a cliff face. Conversely, Trenhaile (2002) investigated the role of weathering and platform width suggesting that platform morphology is largely determined by the tidal control of the distribution and duration of wave energy within the intertidal zone. Low gradient, wide platforms are associated with the high tidal duration during neap tidal heights, whereas steep, narrower platforms occur at spring tidal extremes where tidal duration is low (Trenhaile, 2002).

The width of a platform reaches an equilibrium state where the rate of erosion and the cliff is equal to the rate of erosion at low tide (Trenhaile, 1983). Any changes in mean sea level will alter the gradient and width of a platform until it reaches equilibrium again. Time since the latest change in mean sea level has been long enough to assume that all platforms are at equilibrium (Trenhaile, 2002)

Appendix 2 – Detailed methods

Profiling

Profiling involves taking height and location information along a transect through the site. Profiling was conducted using a Magellan Real-Time Kinematics (RTK) Differential Global Positioning System (DGPS) that has a horizontal and vertical accuracy of approximately 1cm (David Magee pers. comm., July 2008). The offshore limit of the profile was determined by the depth of the water and the conditions, ensuring the electrical equipment and surveyor remained safe. The offshore limit of the profile always extended to at least the top of the low tide cliff or below low low water. The onshore extent of the profile incorporated the highest limit of the primary dune or cliff. The location of the profile was determined by the site of biological sampling (herein after referred to as the *site*), where the transect bisected the middle of the site at an orientation perpendicular to the shore. The distance between points was at the discretion of the surveyor with different substrates and gradients justifying different distances between points of measurement. For example a sandy beach with a low gradient would be sampled every 1-2 meters, compared with a rocky and highly complex notch that would be sampled every few centimetres.

Profiles were plotted in Microsoft Excel. Points were plotted as their distance from the centre of the site; positive values indicate onshore and negative values are offshore of the site. Recorded height from the DGPS could not be used to determine platform height due to inaccuracies with the DGPS and the local geoid. Profile height correction could not be done with standard survey marks as their distribution throughout the study site was incomplete and accuracy questioned. Therefore profile height was corrected to the mean height of the platform (method outlined below).

Elle's Out and Elle's In were not sampled due to their remoteness and time constraints.

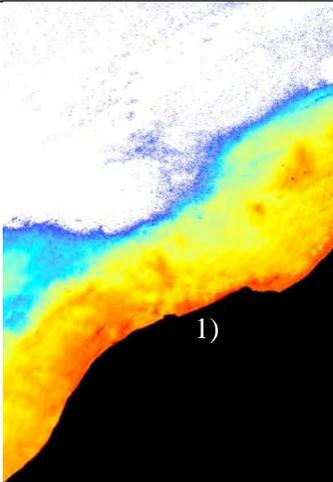
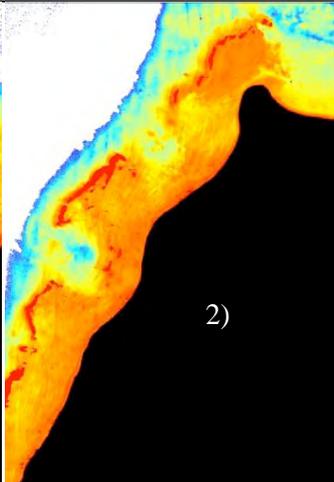
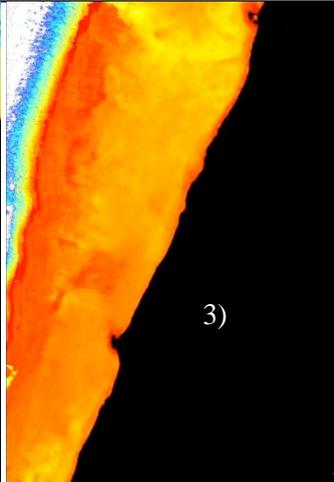
Determining platform height

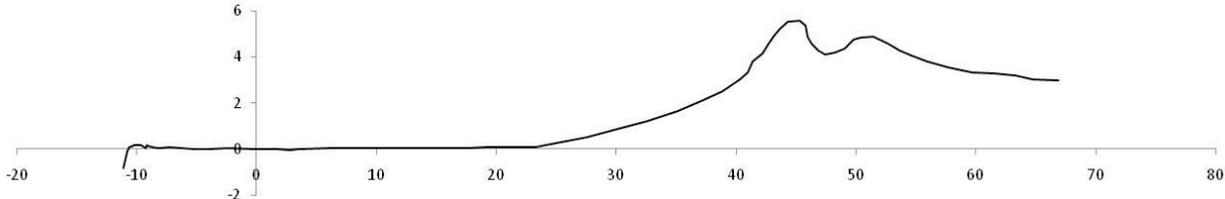
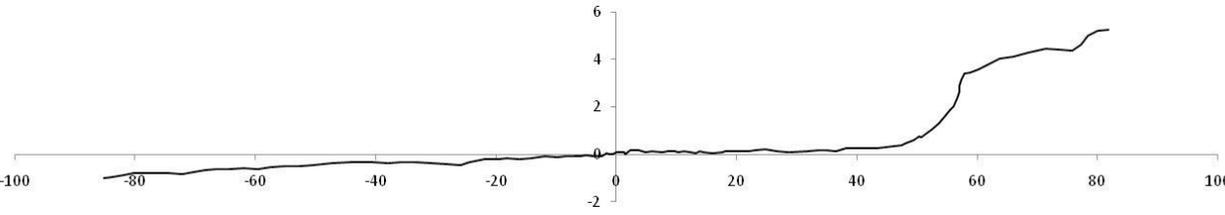
The height of water on the platform was measured using a tape measure and the mean water level was estimated from observing the wave and surge over some minutes. When the water level was lower than the platform a tape measure on a length of weighted chain was used to measure the water level seaward of the platform with the end of the tape measure held at the height of the mean observed water level. The top of an object of known height was placed flat on the site and lined up with the horizon to achieve a level imaginary line. The height at which this line intersected the tape measure was recorded and the known height of the object on the platform subtracted. The final value was the height of the platform relative to the current observed mean water level.

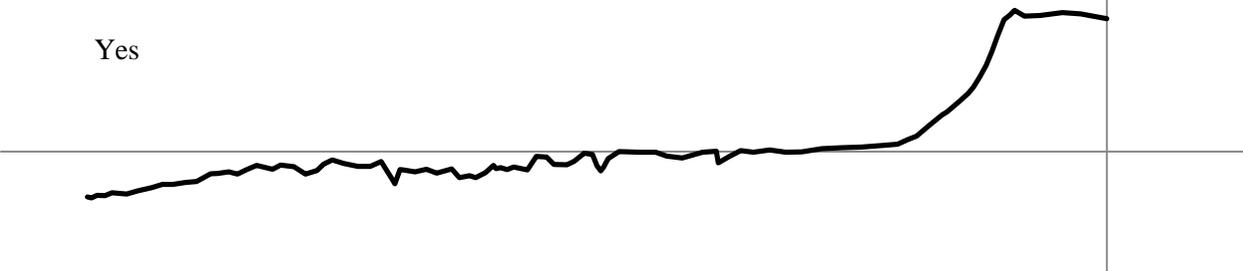
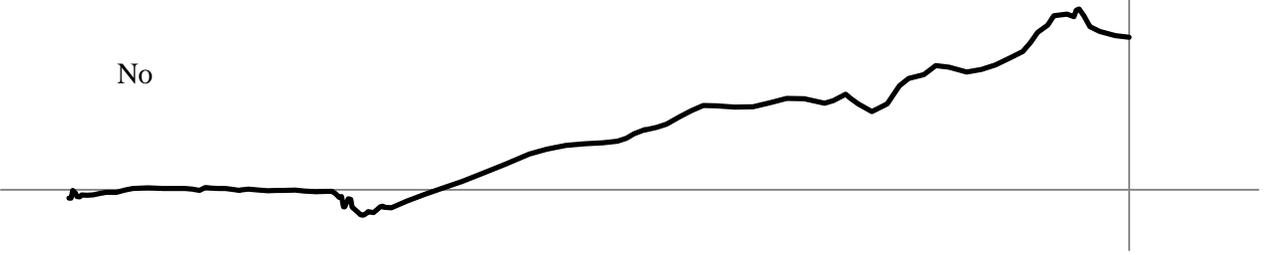
The height of the platform relative to the observed average water level was then corrected using interpolated tidal heights for the local area. To account for residual water level fluctuation⁷, water level data for Exmouth and Canarvon was obtained from the Department of Transport. Investigation into any relationships between the two stations identified that residual water level was behaving differently at each location and an average of the two stations could not be used to correct heights at all sites. Instead the residual water level from the nearest station to each site was used. The residual water level data was then added or subtracted from the tide corrected platform height to achieve the final platform height (m CD).

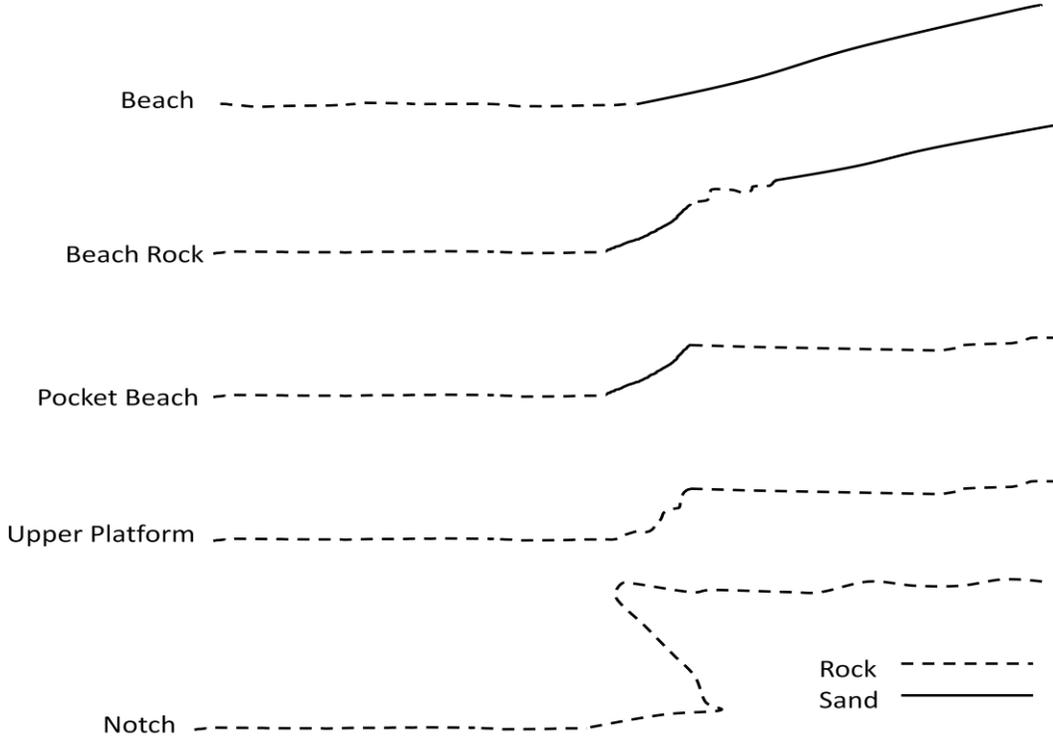
⁷ Residual water level is that not accounted for by the tide. Also known as surge it results from wave and wind setup and setdown and atmospheric pressures.

Platform attributes

Section	Attribute	Examples	
Fringing reef	<ol style="list-style-type: none"> 1. None 2. Discontinuous 3. Continuous 	 <p>1)</p>	 <p>2)</p>  <p>3)</p>
Lagoon substrate	<ol style="list-style-type: none"> 1. Pavement 2. Sand 	 <p>1)</p>	 <p>2)</p>

<p>Platform edge</p>	<p>1. Low tide cliff 2. Grading</p>	<p>1) </p> <p>2) </p>
<p>Sand veneer</p>	<ul style="list-style-type: none"> • Yes • No 	<div style="display: flex; justify-content: space-around;"> <div style="text-align: center;">  <p>Yes</p> </div> <div style="text-align: center;">  <p>No</p> </div> </div>
<p>Cobbles/boulders</p>	<ul style="list-style-type: none"> • Yes • No 	<div style="display: flex; justify-content: space-around;"> <div style="text-align: center;">  <p>Yes</p> </div> <div style="text-align: center;">  <p>No</p> </div> </div>

<p>Platform adjoined to shore</p>	<ul style="list-style-type: none"> • Yes • No 	<p>Yes</p>  <p>No</p> 
<p>Ramp</p>	<ul style="list-style-type: none"> • Yes • No 	 <p>Yes</p> <p>No</p>

<p>High water interface</p>	<ul style="list-style-type: none"> • Beach • Beach rock • Pocket beach • Upper platform • Notch 	 <p>The diagram illustrates five coastal features from top to bottom: Beach, Beach Rock, Pocket Beach, Upper Platform, and Notch. Each feature is represented by a horizontal line. A legend indicates that dashed lines represent 'Rock' and solid lines represent 'Sand'. The Beach feature shows a dashed line that is mostly flat but has a slight dip. The Beach Rock feature shows a dashed line that is flat and then has a sharp upward step. The Pocket Beach feature shows a dashed line that is flat and then has a sharp downward step. The Upper Platform feature shows a dashed line that is flat and then has a sharp upward step. The Notch feature shows a dashed line that is flat and then has a sharp downward step.</p>
<p>Dune</p>	<ul style="list-style-type: none"> • Vegetated • None 	 <p>Two photographs of dunes are shown side-by-side. The left photograph shows a dune with a sandy slope and sparse vegetation, labeled 'Vegetated'. The right photograph shows a dune with a sandy slope and no vegetation, labeled 'None'.</p>

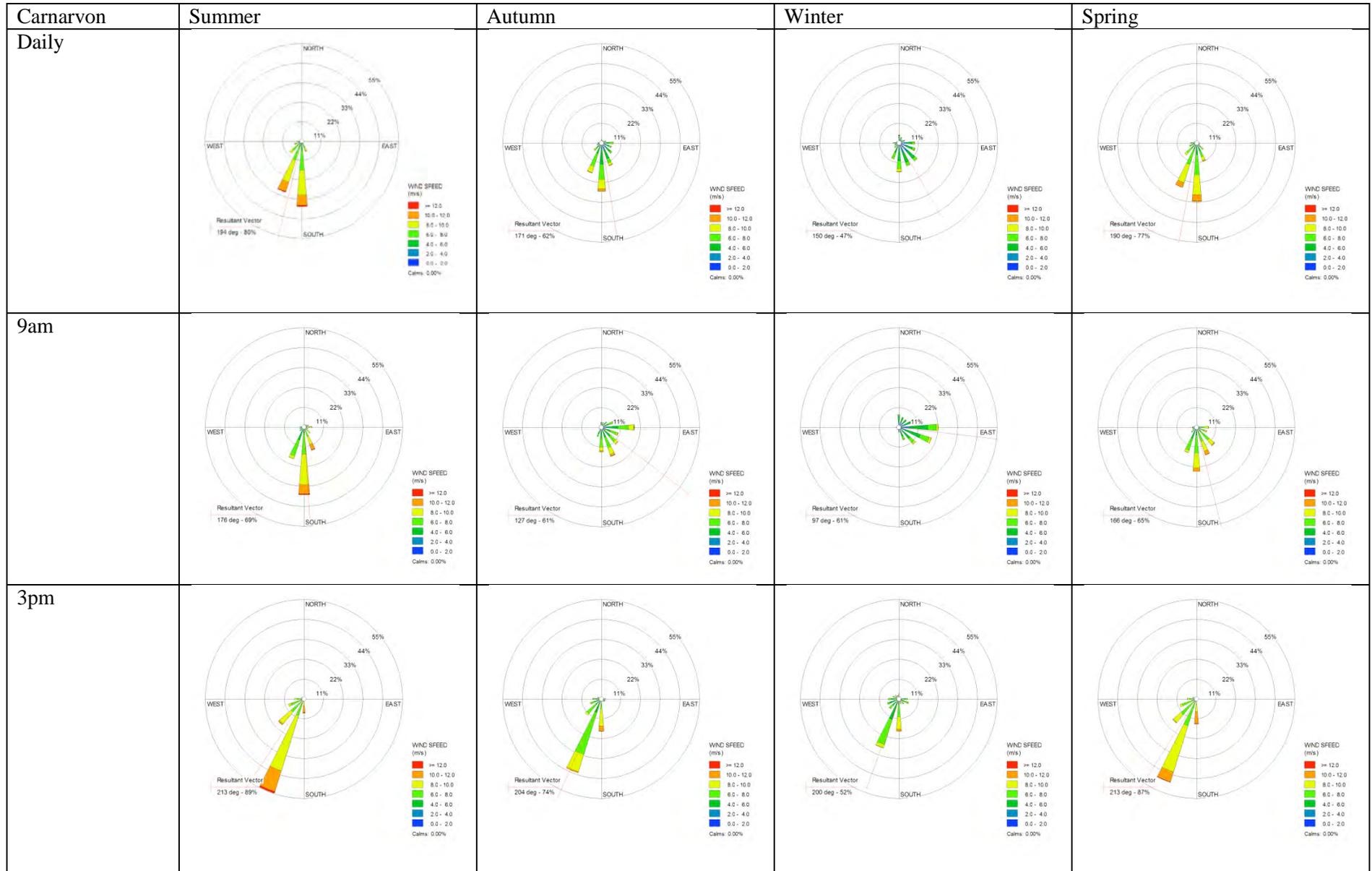
Invertebrate sampling

Intertidal invertebrate assemblage data was sampled during two field trips; one in July (northern sites) and another September (southern sites) 2009. Sampling was primarily conducted by Robert Black, Mike Johnson, Jane Prince and Anne Brearley (herein after referred to as the *WAMSI team*) with assistance from the author. Preliminary sampling by the WAMSI team in 2007 identified that most of the animals were sedentary or sessile and comprised primarily of gastropods, bivalves, chitons, echinoderms and cnidarians. In light of this it was decided that all individuals would be counted in replicated 1m² quadrats. Four 50 x 50 cm quadrats were used to define each 1 m² quadrat as they provided smaller boundaries that made counting animals easier and were more transportable than 1 x 1m quadrats. Quadrat location within the 15m wide by 50m long sampling site was determined by throwing one quadrat far enough ahead so as not to see what would be within it. The remaining three were placed around the thrown quadrat to make a square. Sampling began at one end of the site moving to the opposite end, generally sampling ten quadrats in this space. To complete 10 more quadrats totalling 20, sampling was completed in the opposite direction. This method of sampling ensured coverage of the entire platform and is likely to be patterned rather than completely random.

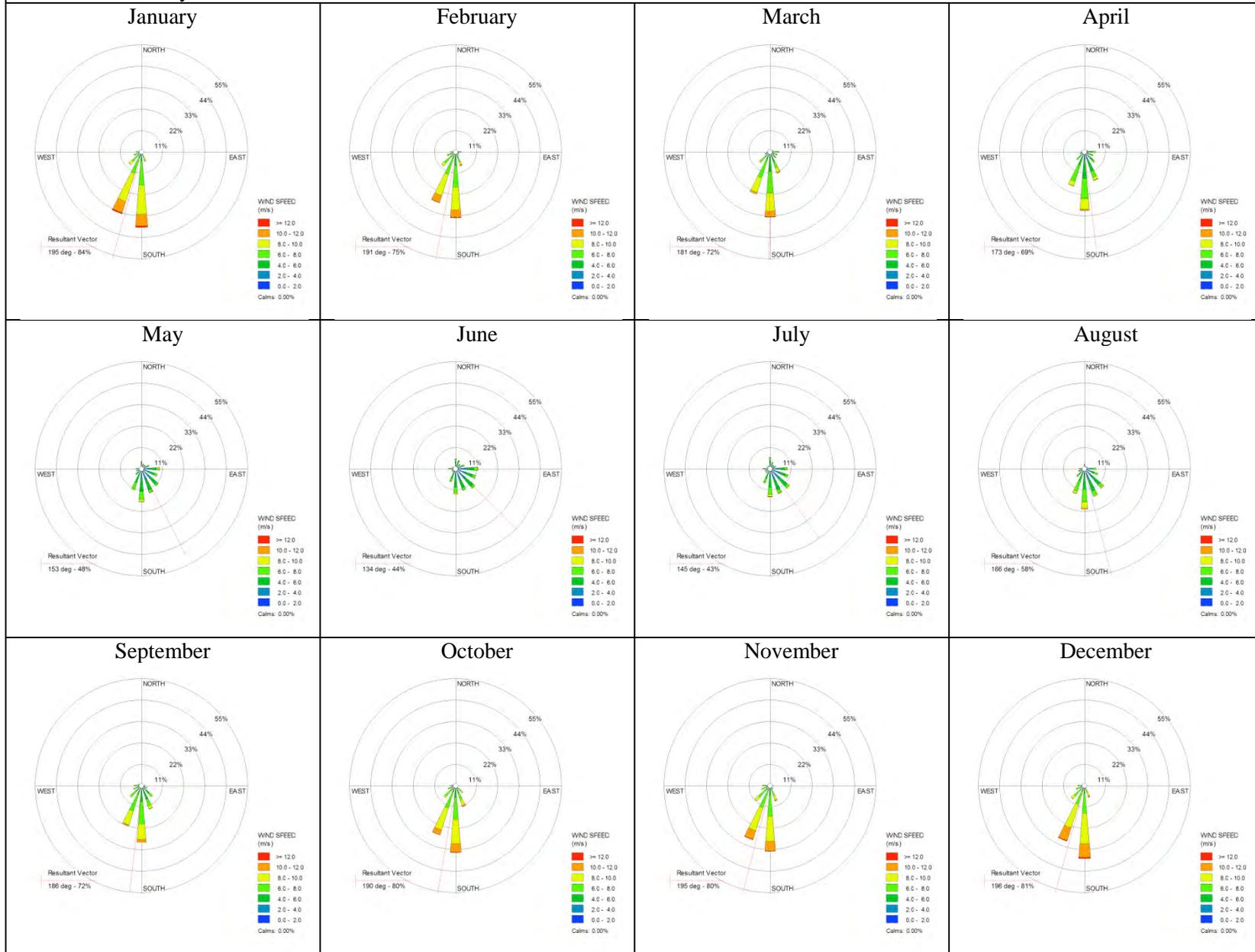
Usually two persons worked together to identify and count all invertebrates in the quadrats. Animals were found by feeling for moveable objects on the surface of the platform, within crevices and under overhangs and sediment was sifted through. Two or more searches of the quadrat were undertaken generally from a different position to ensure all animals were spotted. A mental tally of sessile individuals was kept but all unattached individuals were collected into a bucket and identified and counted at the end of the search of the quadrat. Species were identified using a field identification guide developed by the WAMSI team and a number of other identification guides. Heads of coral were scored as one and hermits were recorded as presence/absence as species identification in the field is difficult. A voucher was taken for all new species and those that could not be identified in the field such as soft corals.

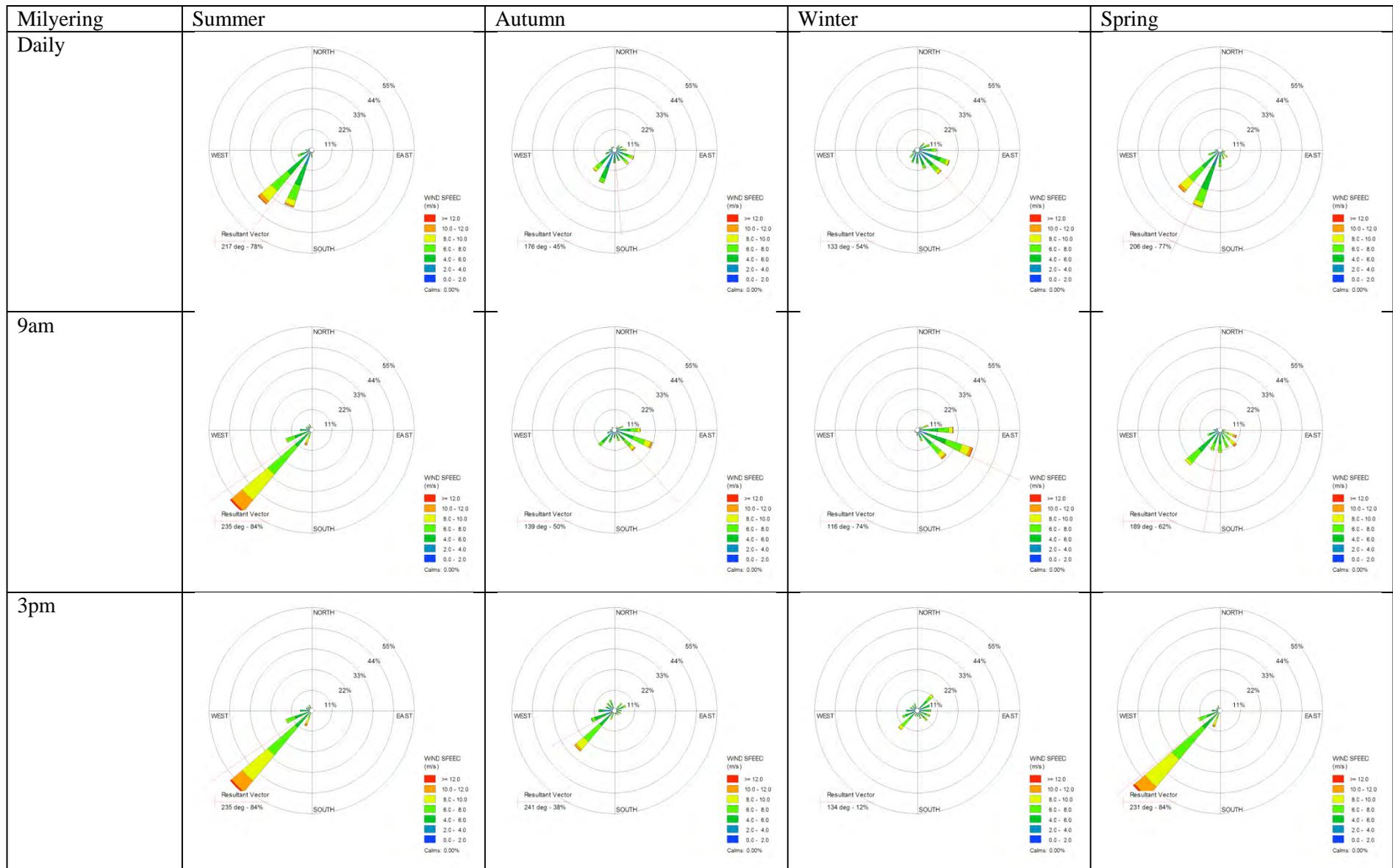
Data were recorded by the same person for a site to ensure the consistency in species identification and that vouchers were recorded accurately. The recorder was also responsible for taking photos of new species and taking general notes such as the sampling start and end time. Data were transcribed from field sheets to a spreadsheet template as soon as possible upon returning from the field.

Appendix 3 – Wind roses.

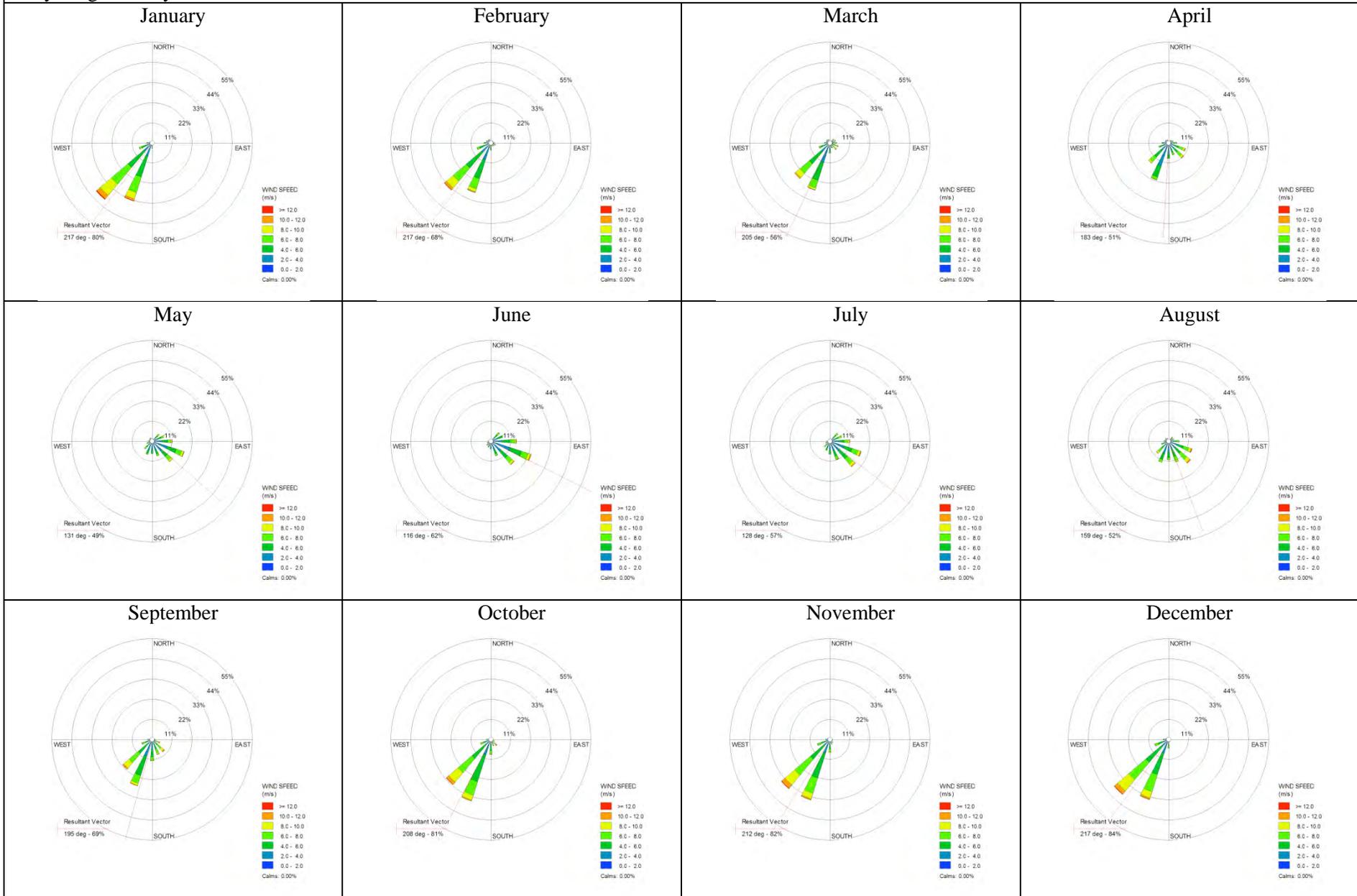


Carnarvon monthly wind roses



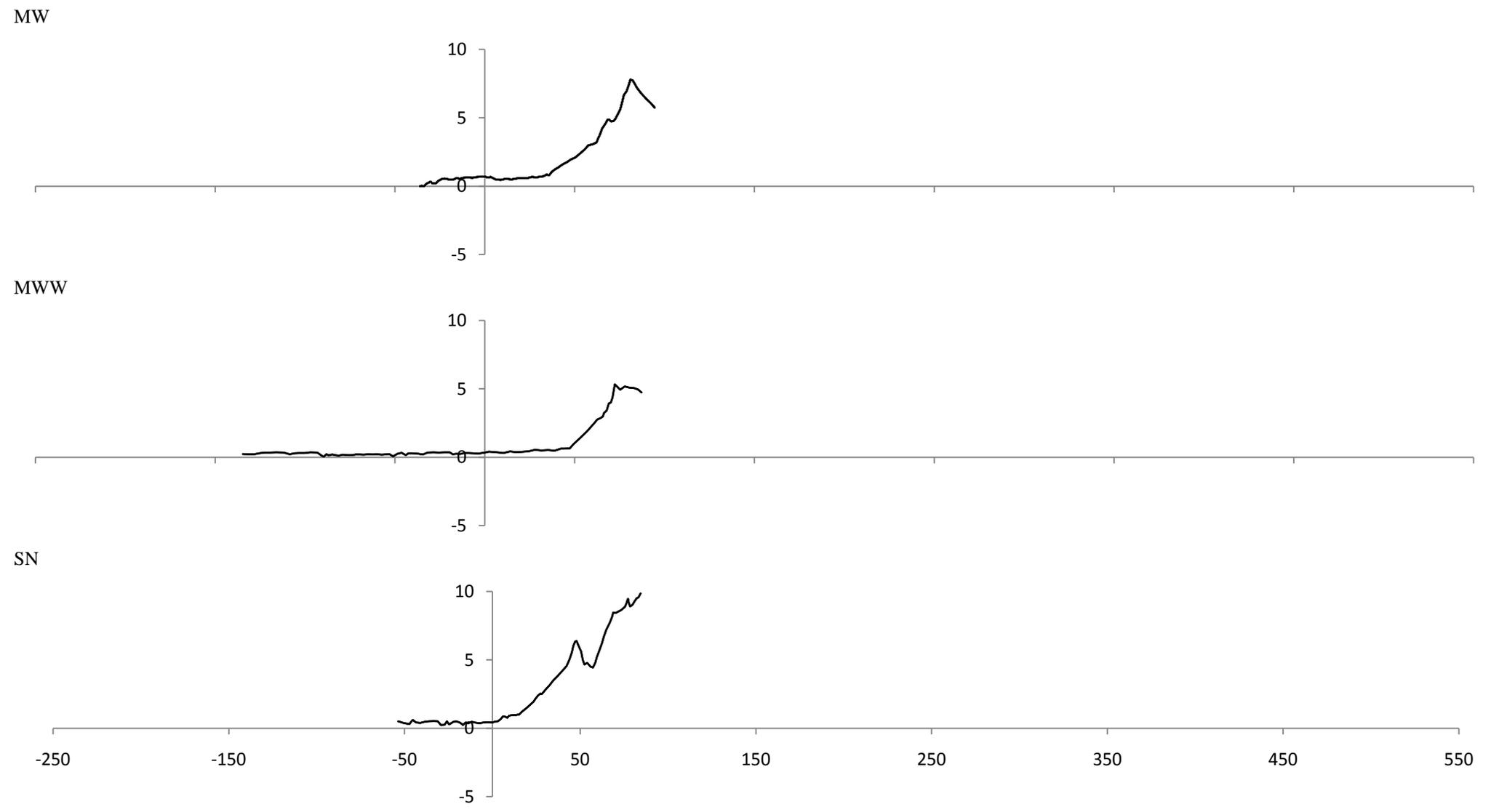


Milyering monthly wind roses

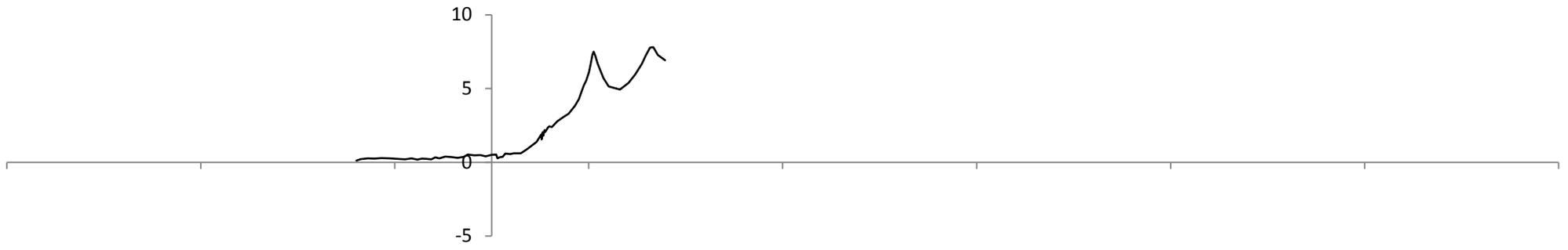


Appendix 4 – Site profiles.

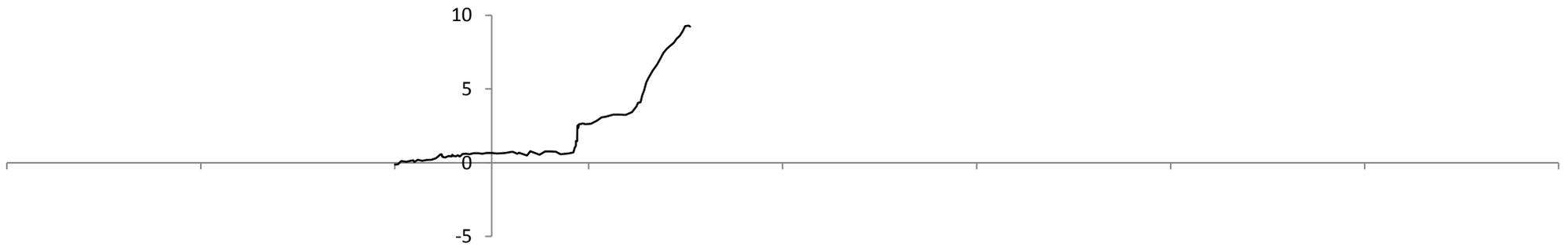
Broad scale



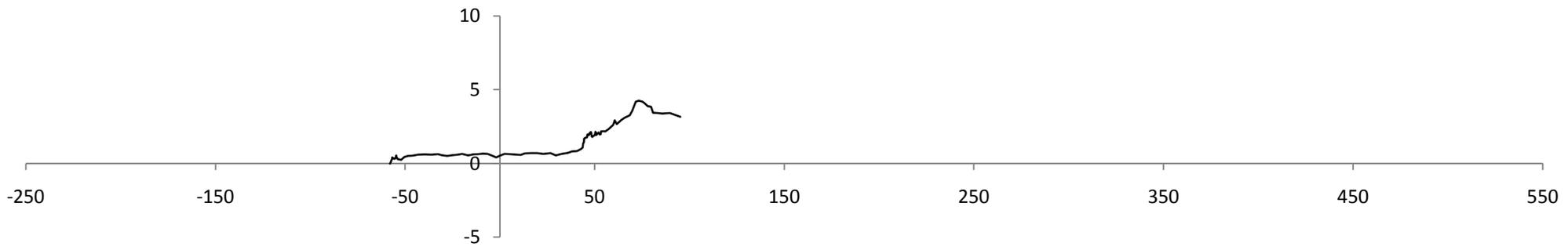
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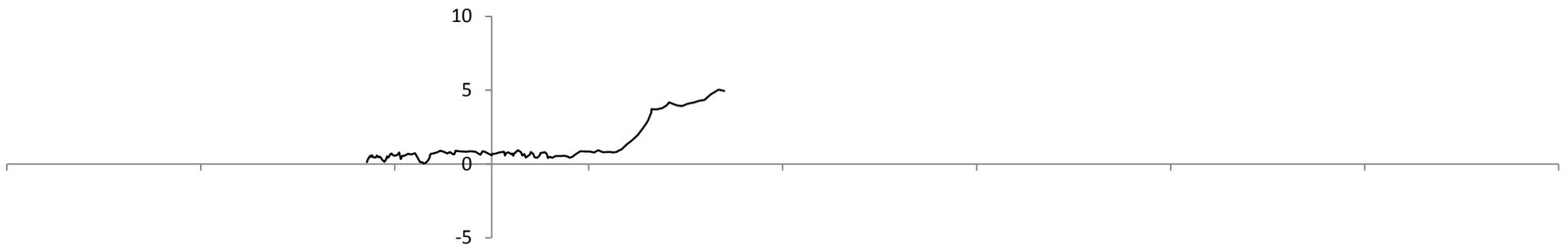
JO2



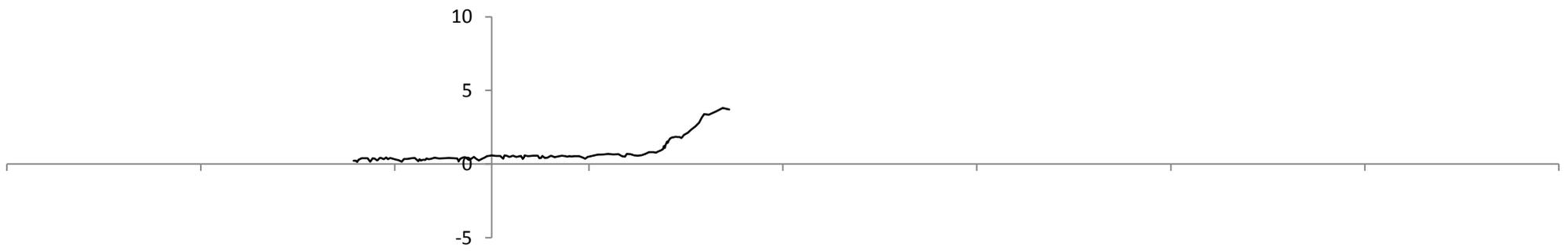
JO1



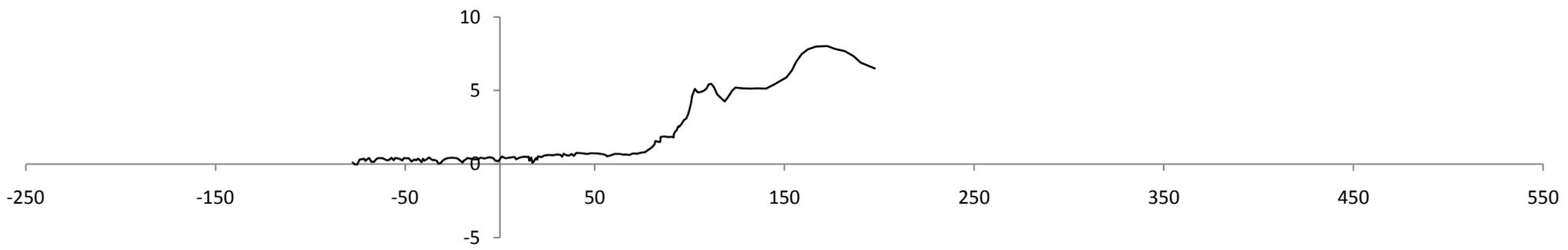
J11



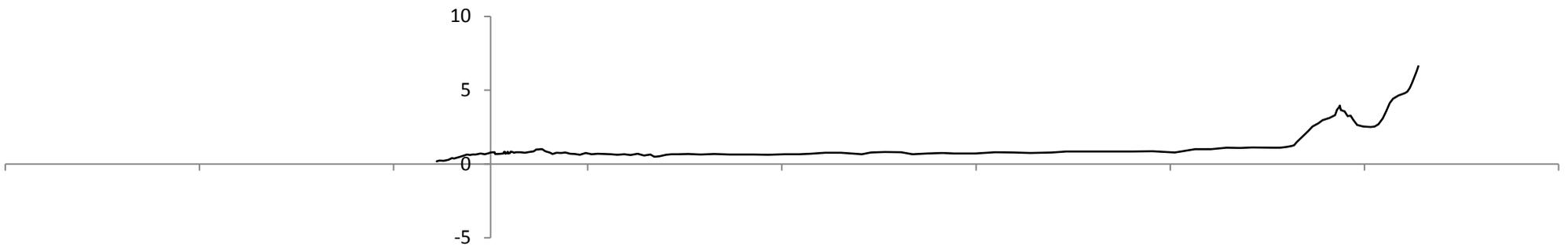
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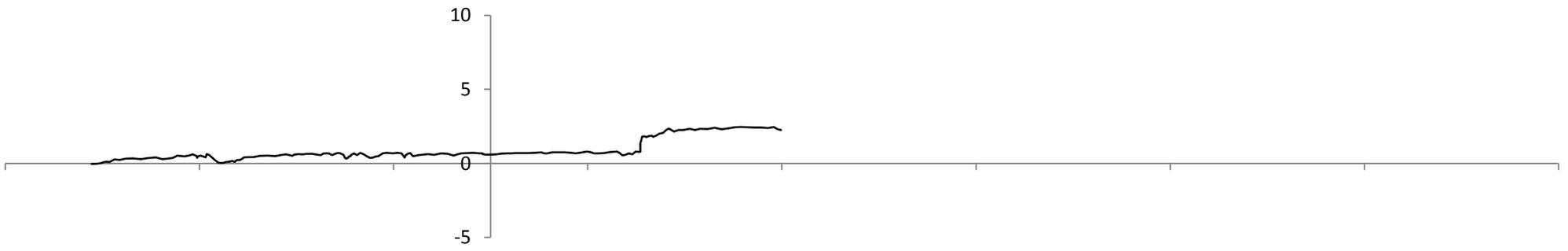
J13



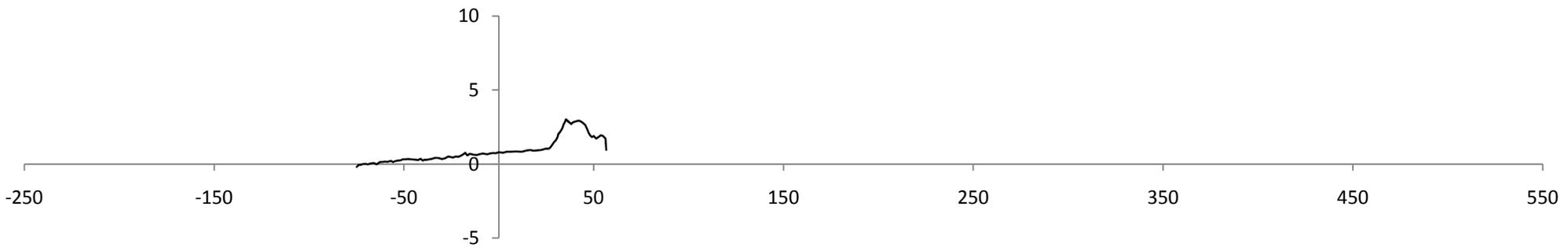
MB



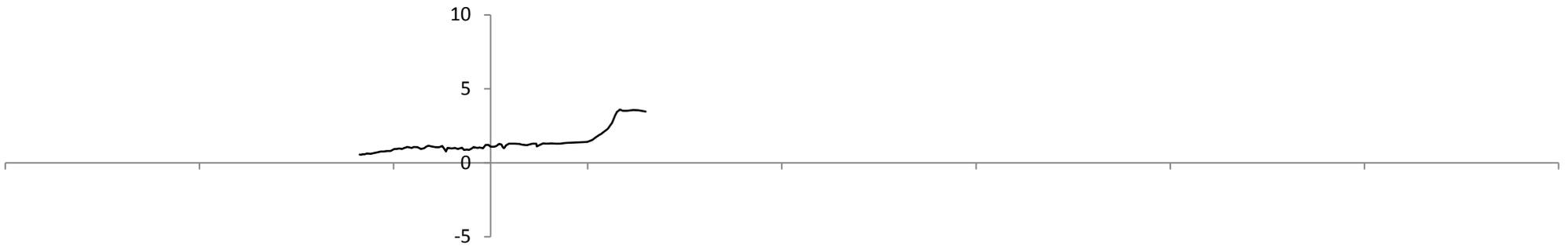
MP



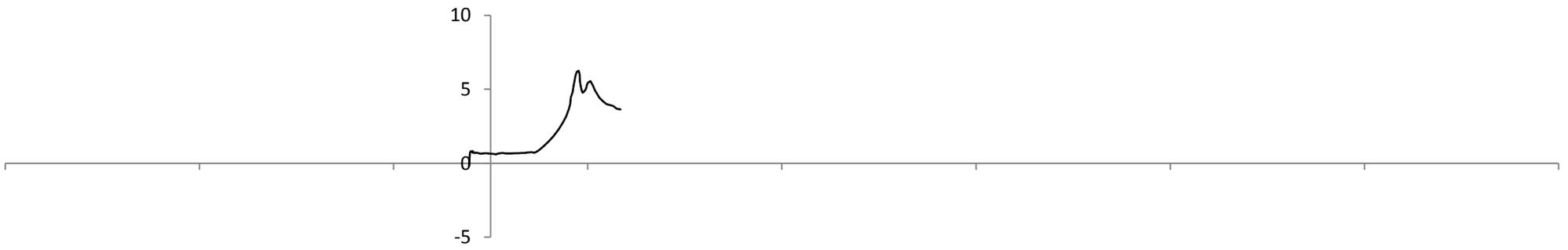
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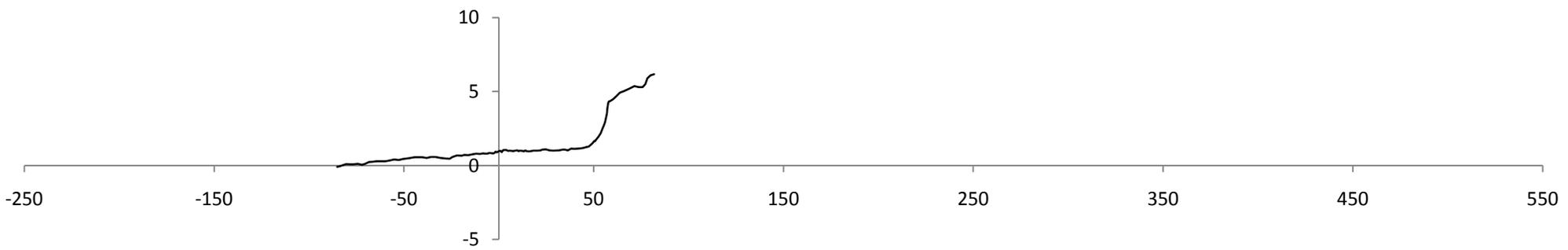
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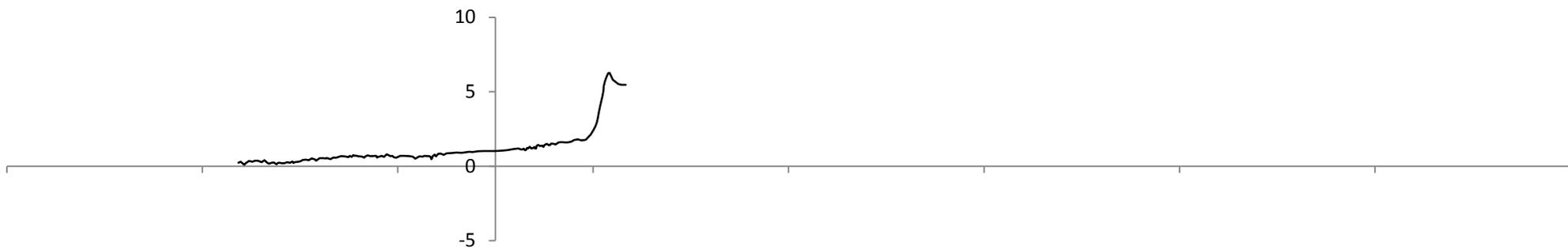
PIL



YCN



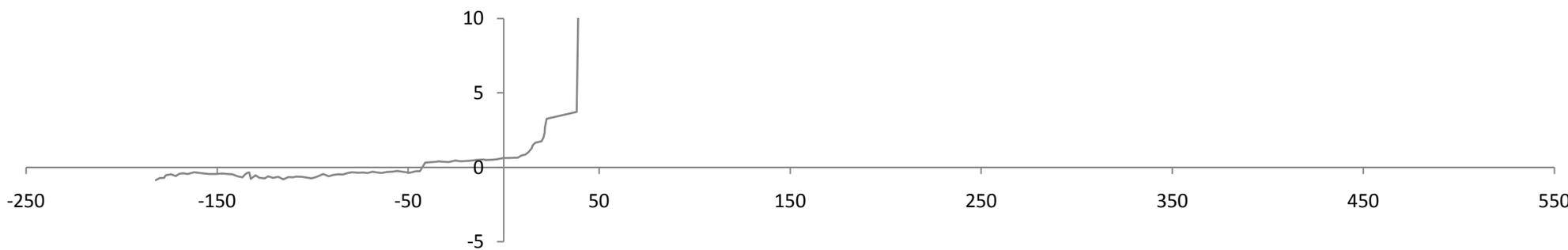
YCS



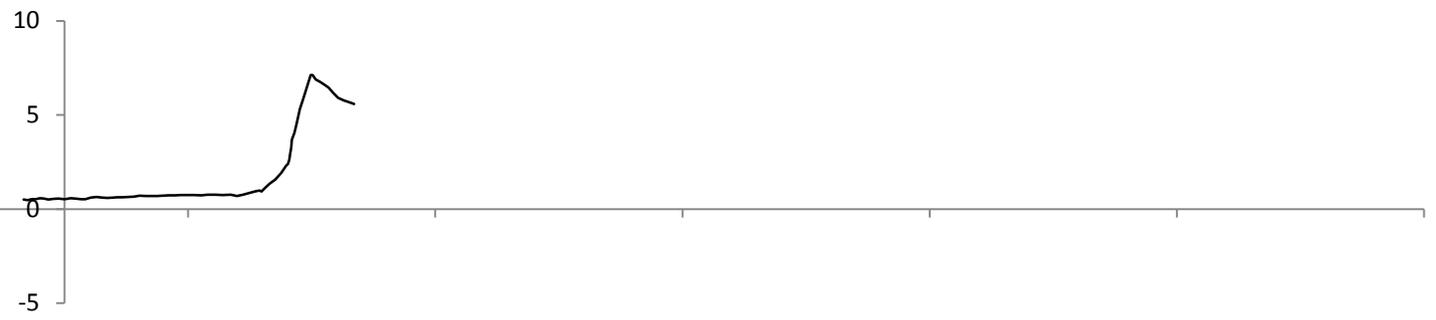
BB02



BBO1



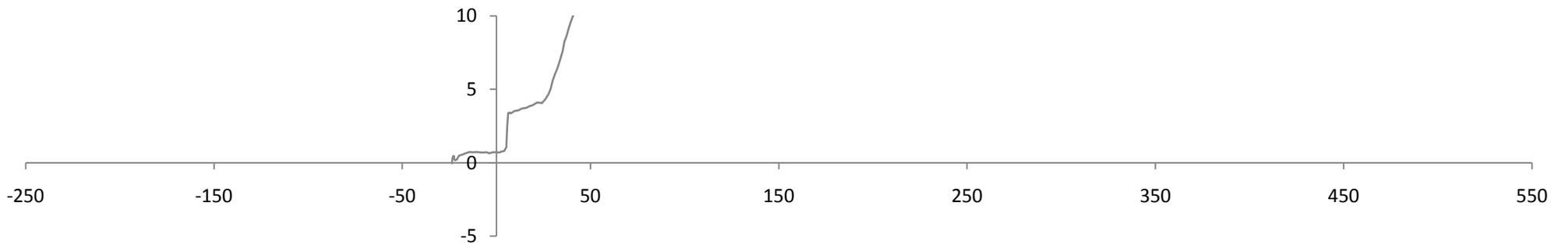
BBI



CBN



CBS



GBO2

10
5
0
-5



GBO1

10
5
0
-5



GBI2

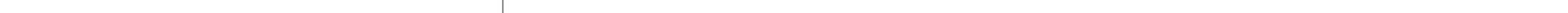
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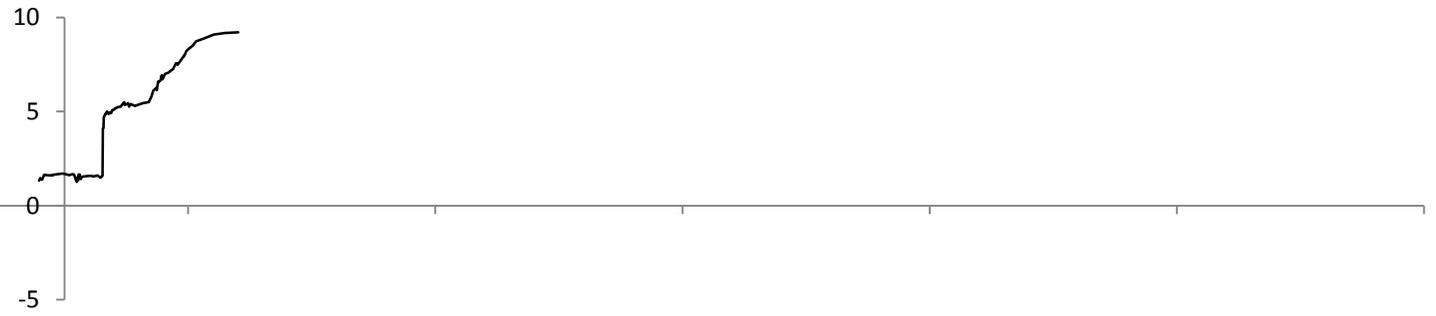
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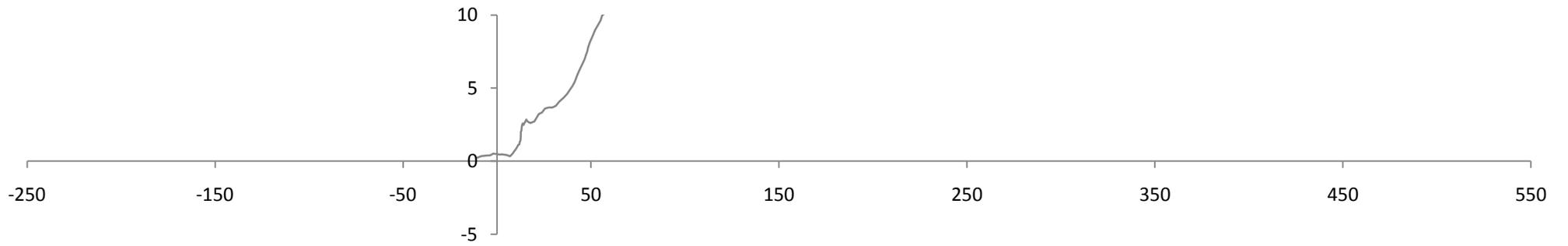
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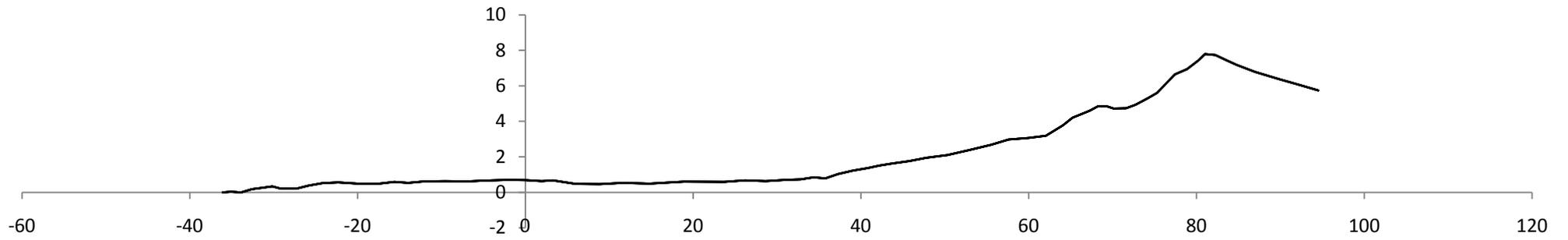


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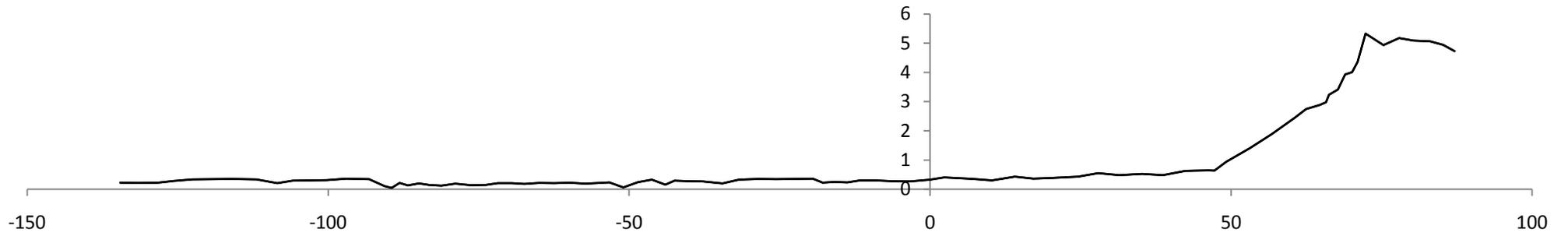


Fine scale

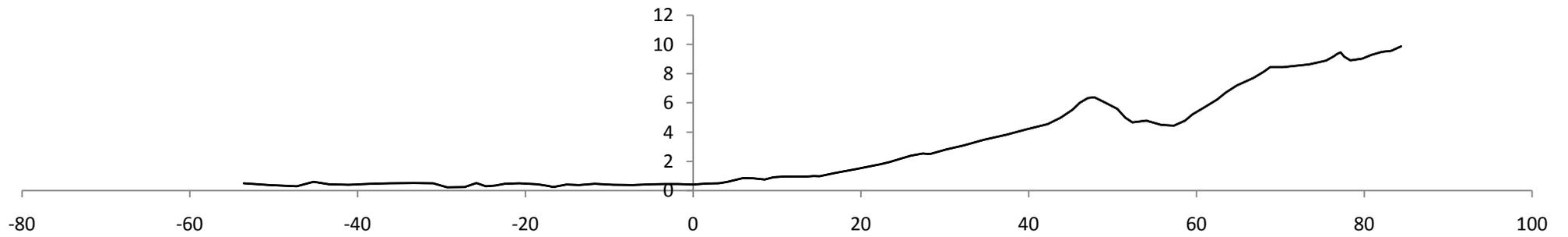
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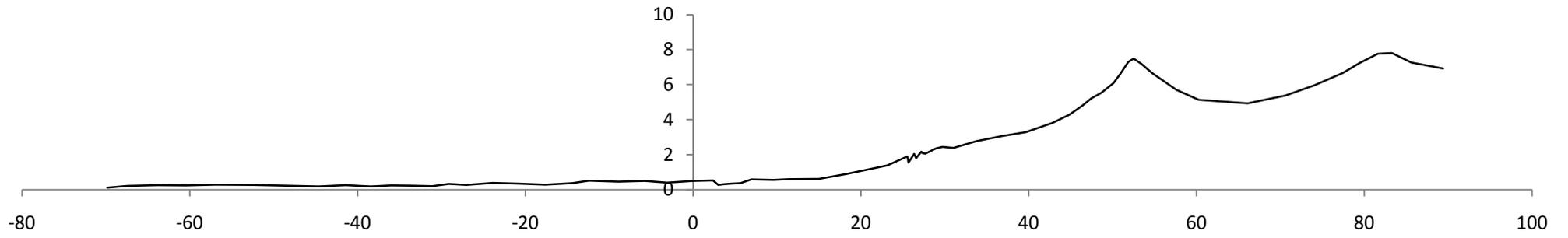
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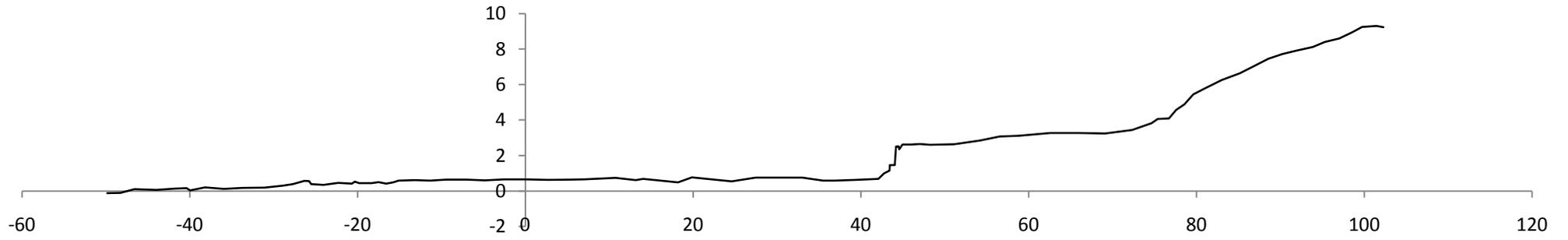
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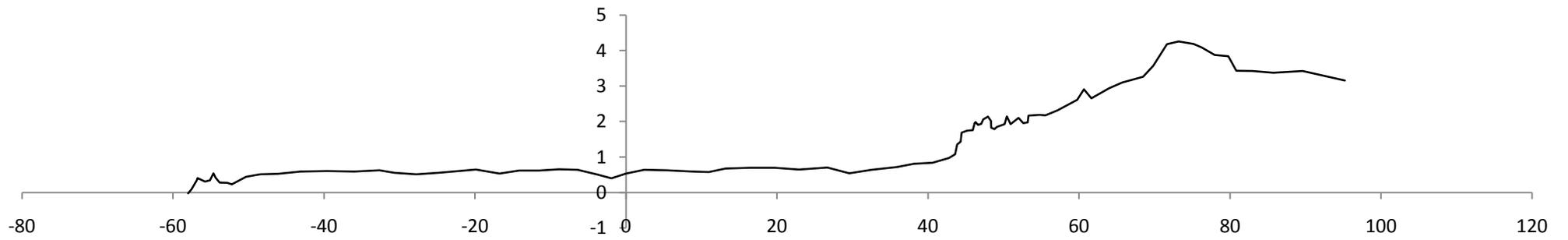
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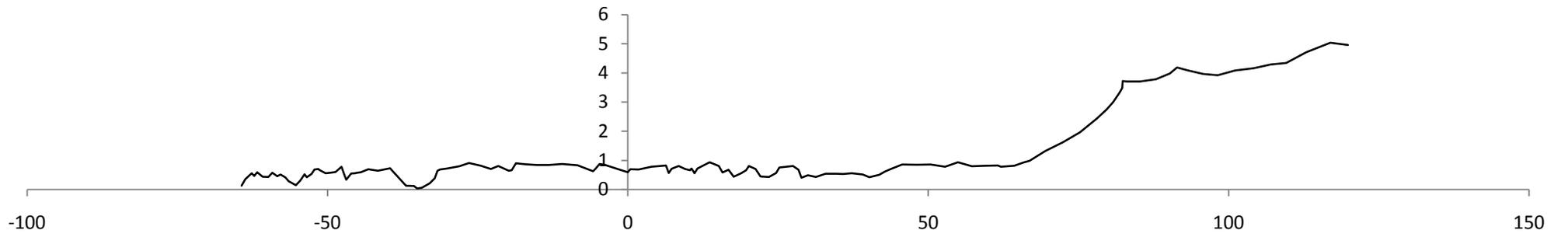
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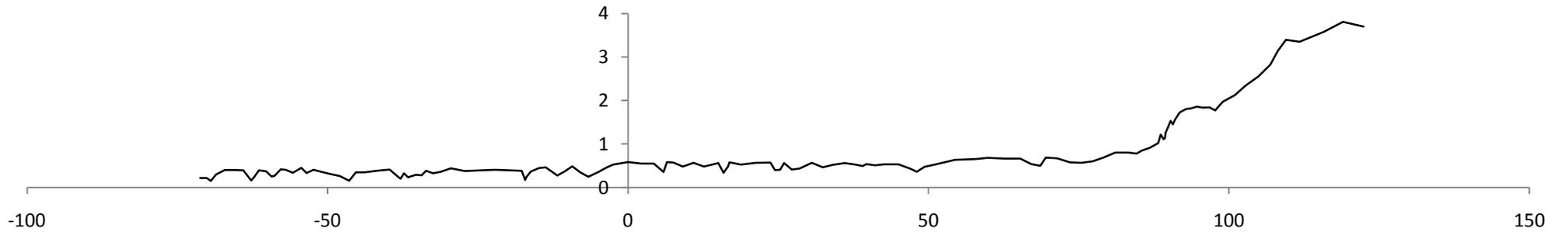
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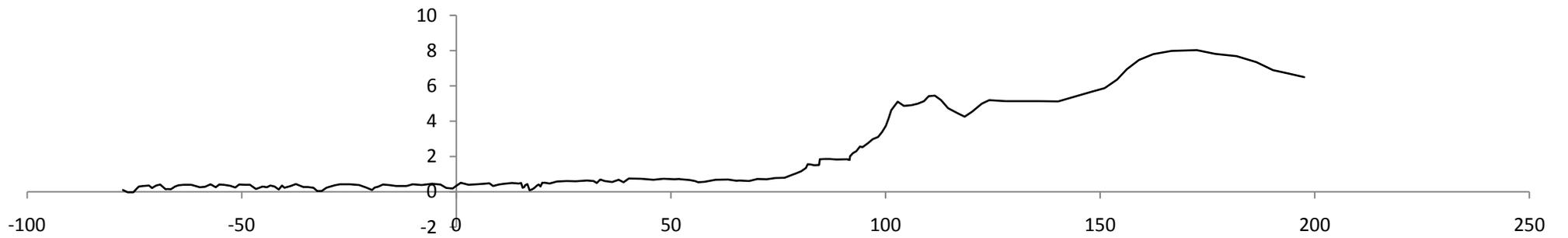
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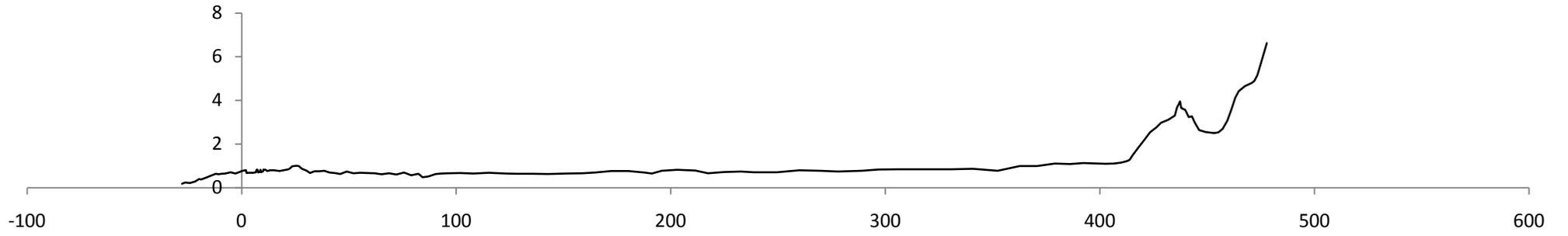
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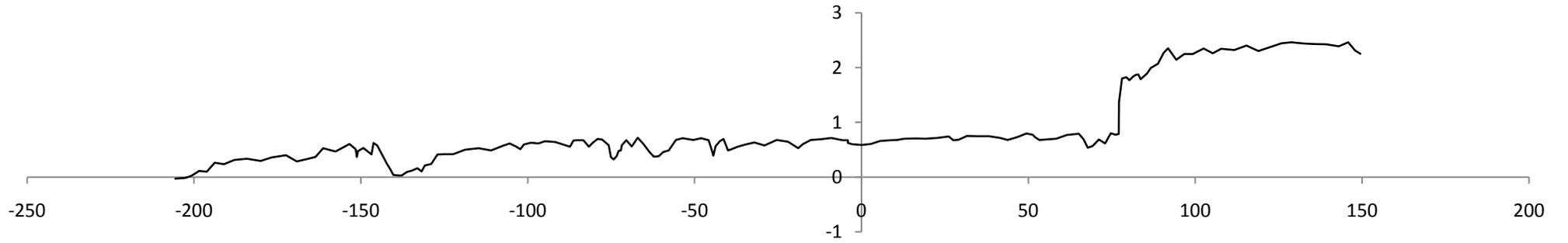
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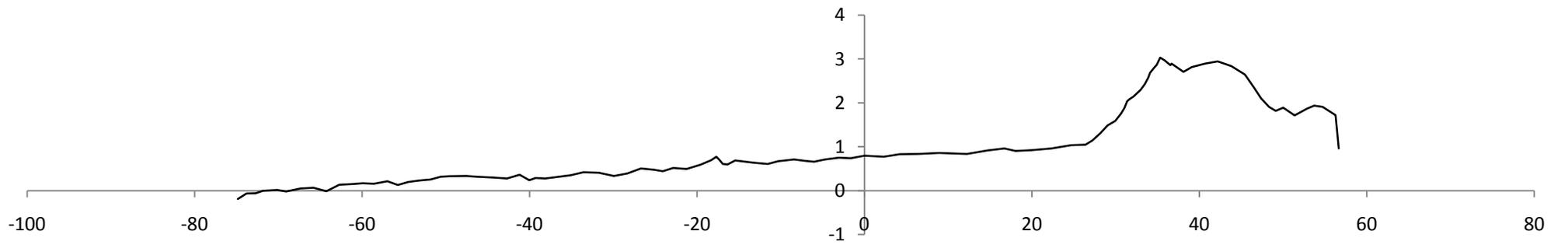
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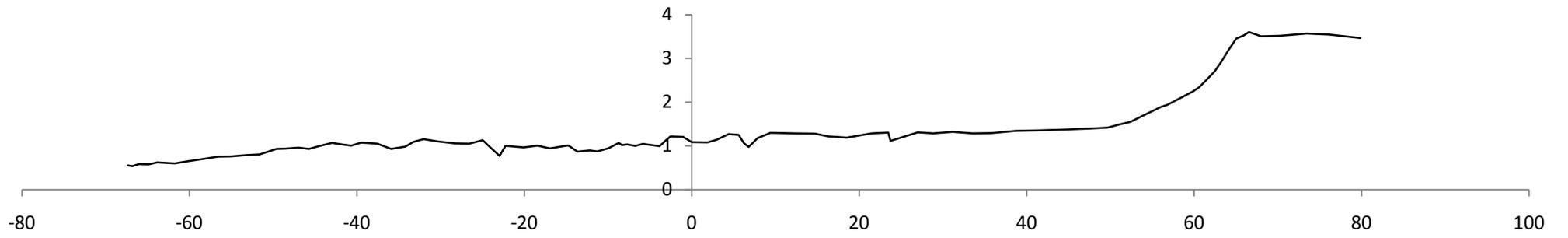
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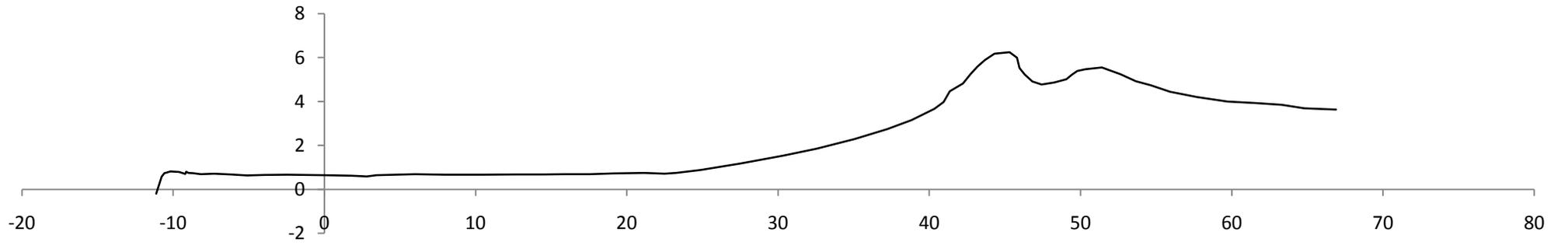
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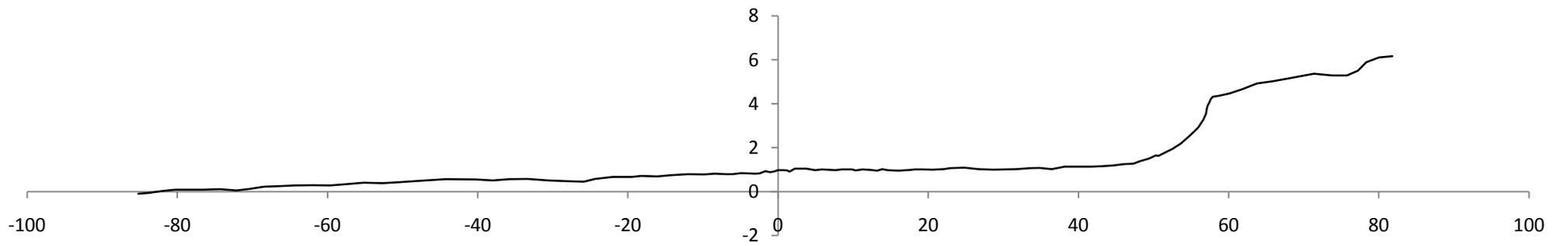
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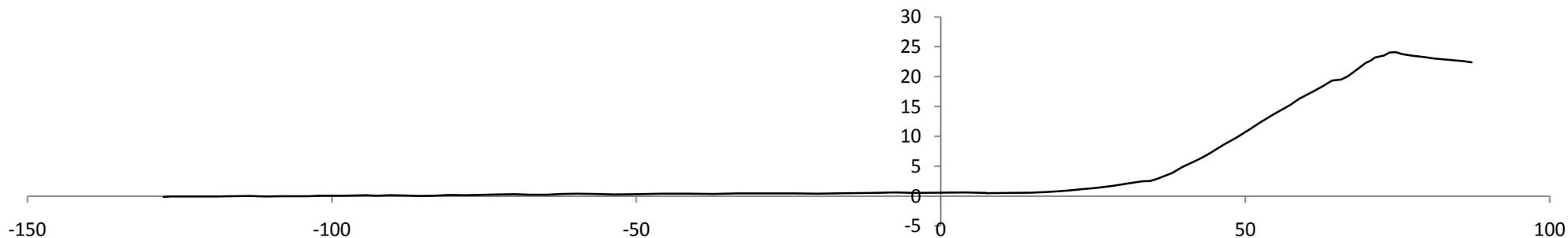
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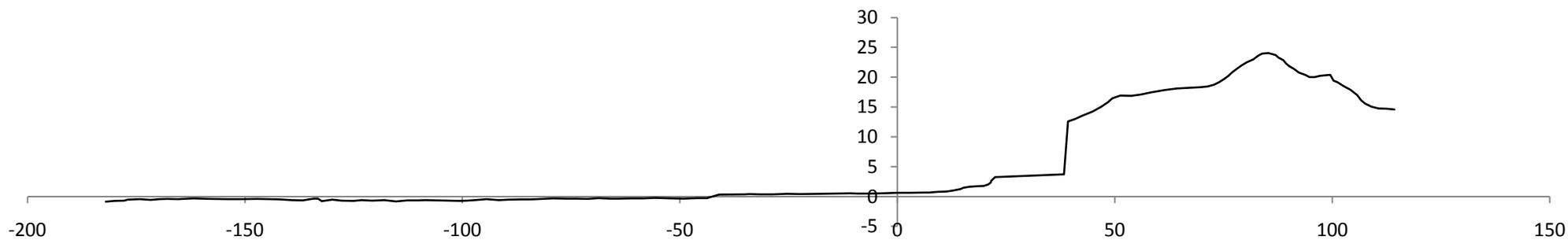
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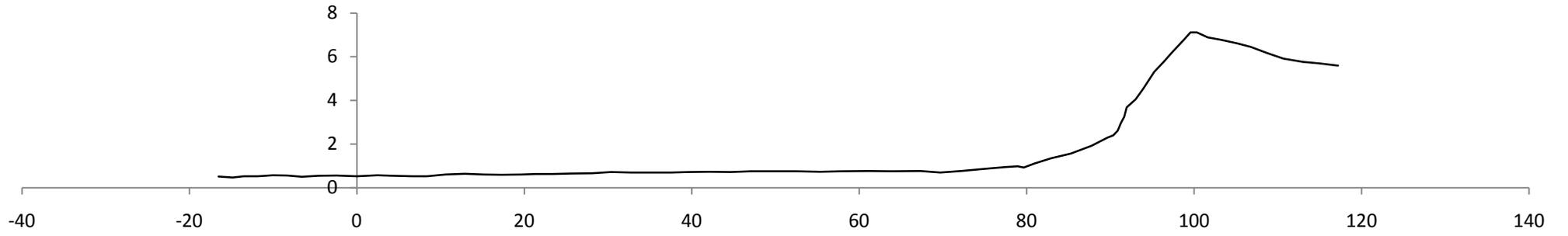
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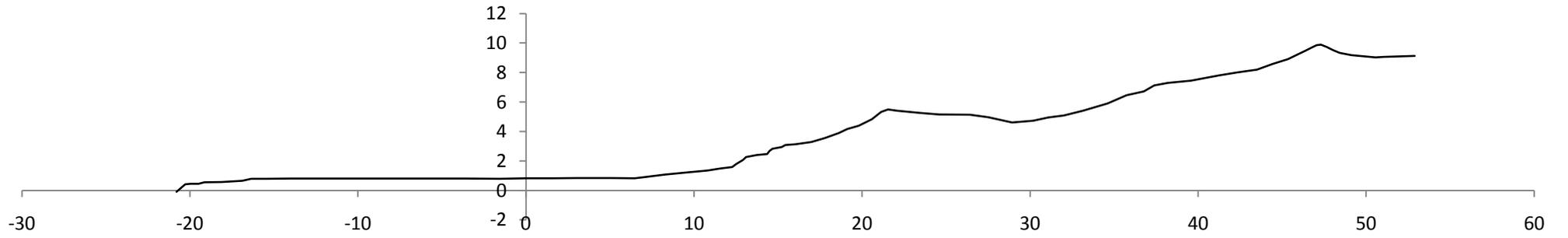
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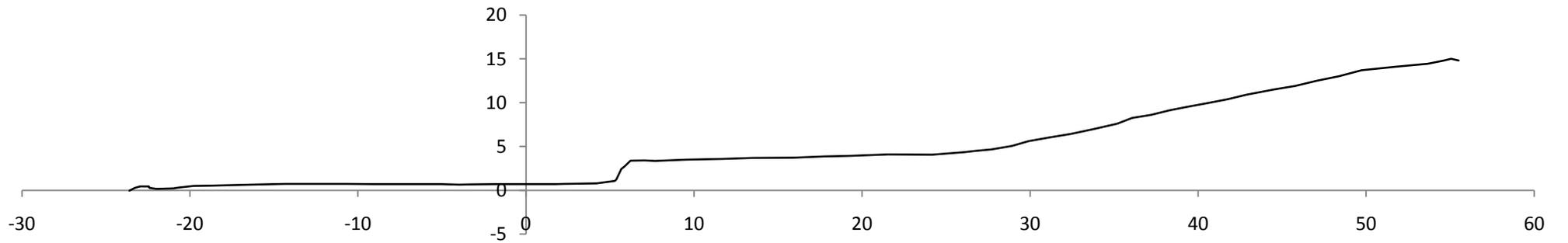
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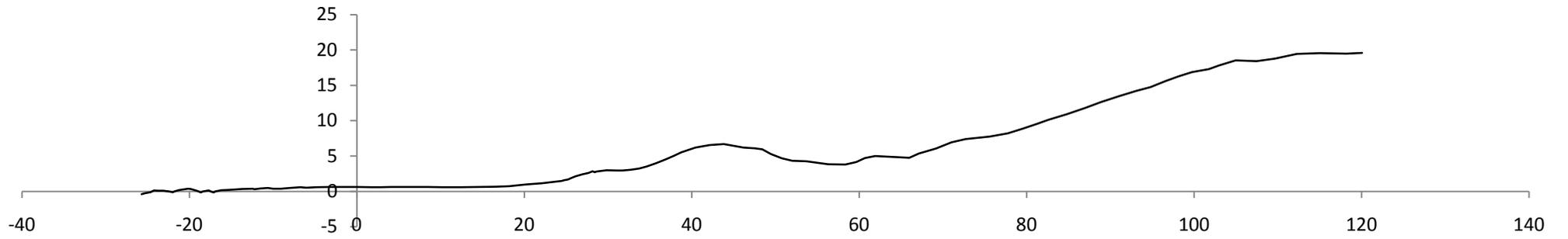
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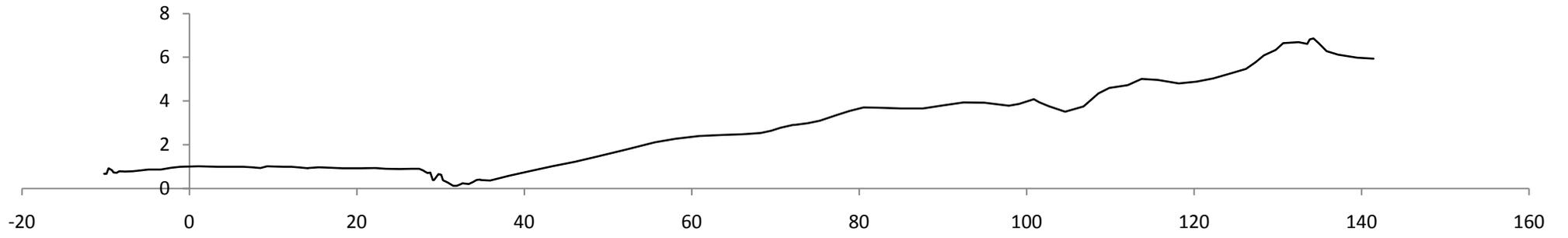
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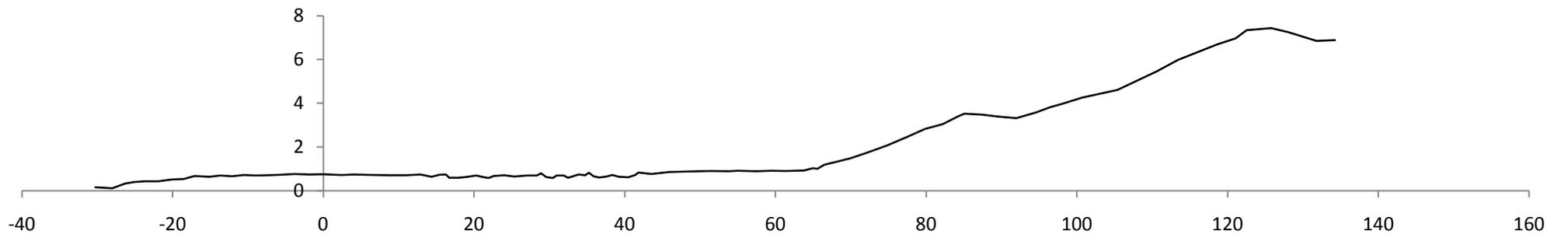
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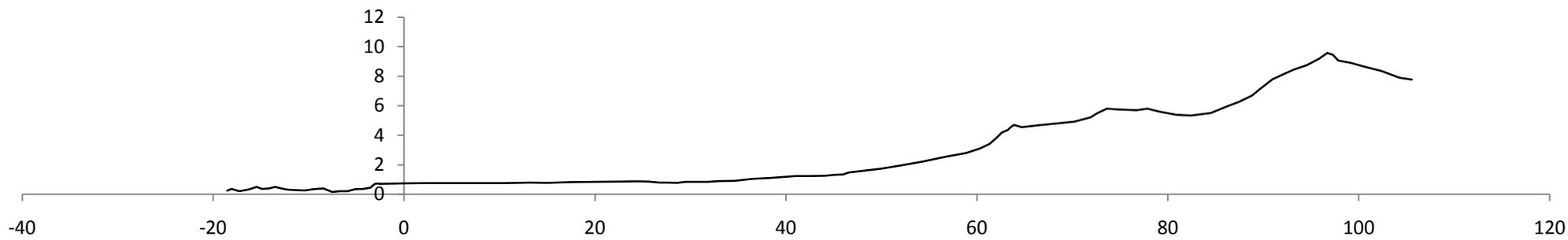
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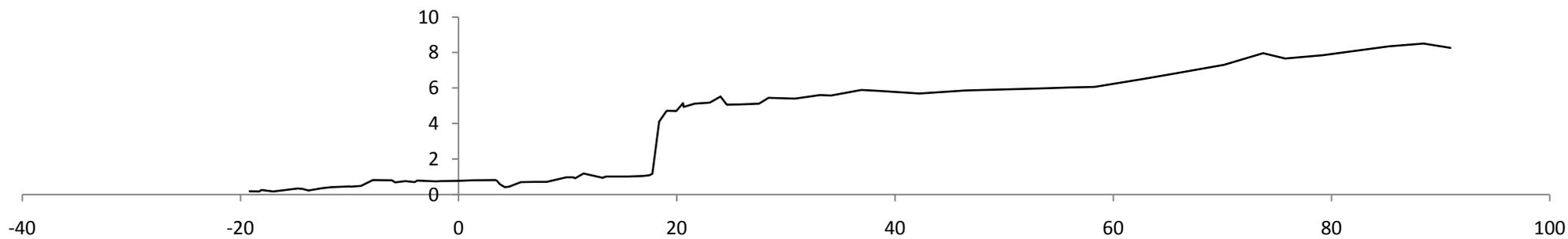
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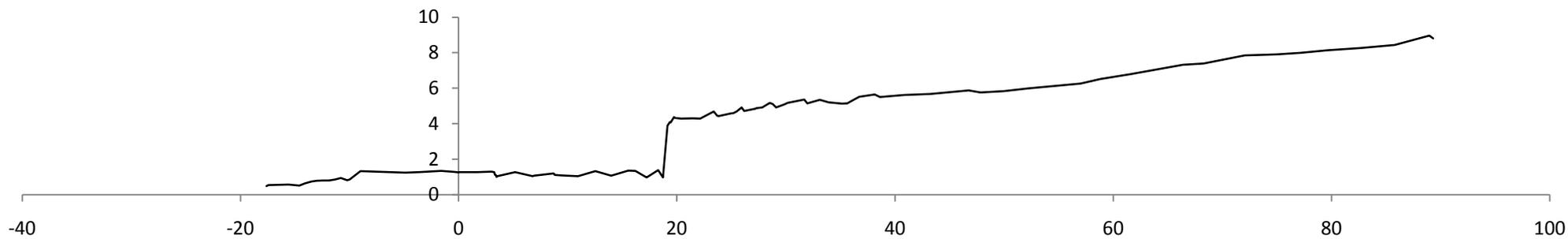
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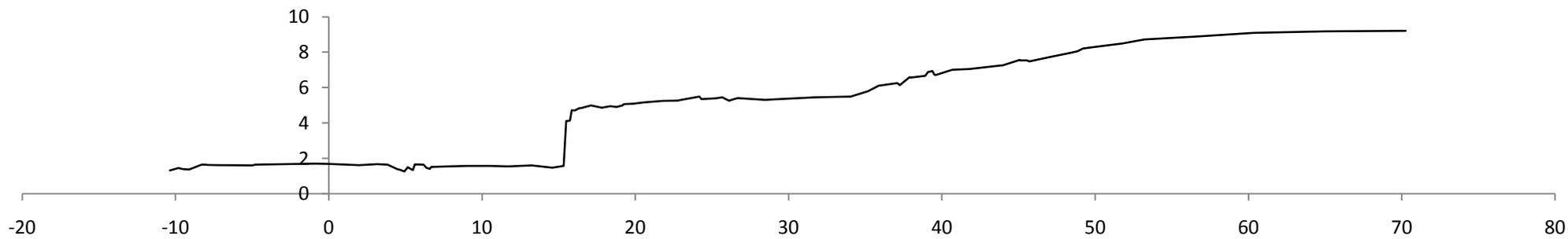
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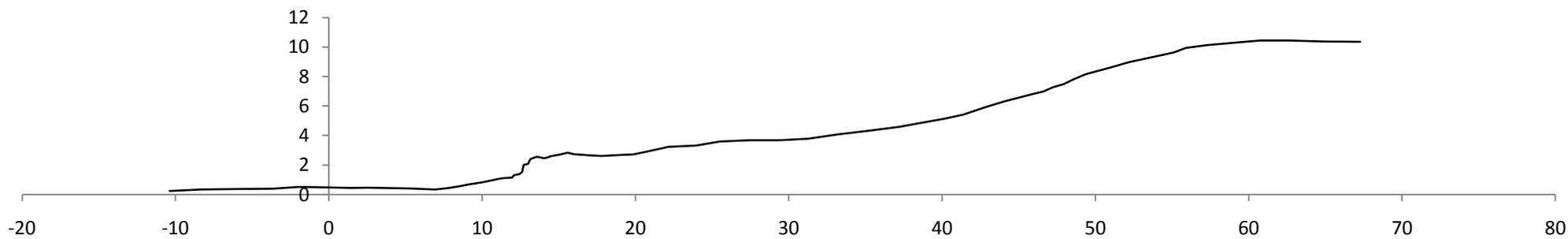
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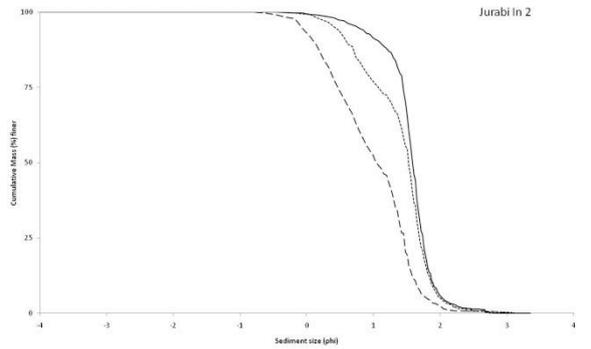
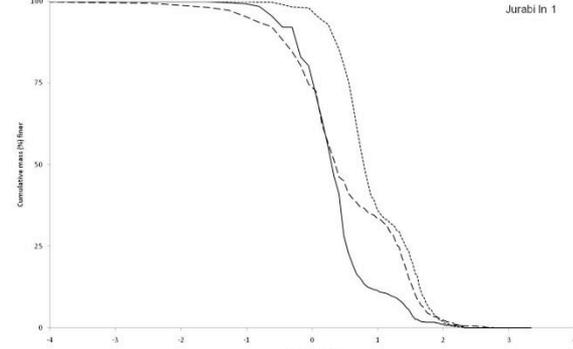
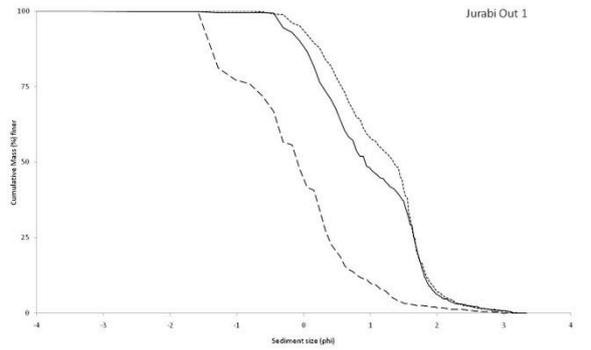
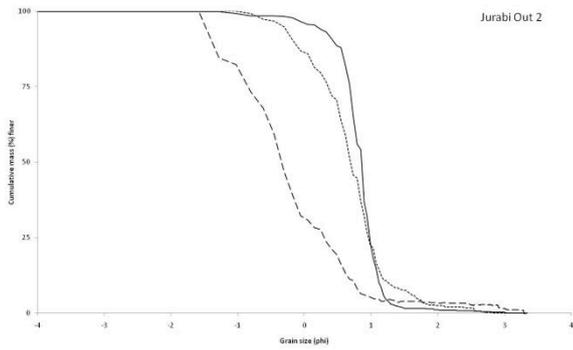
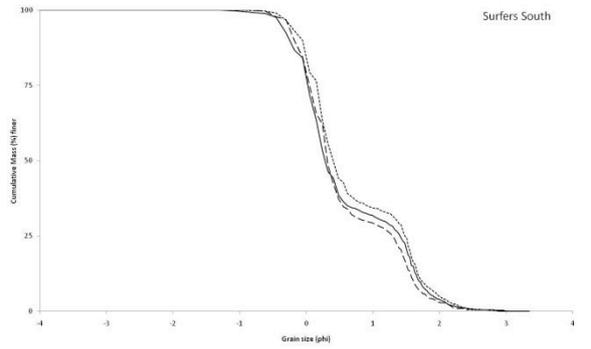
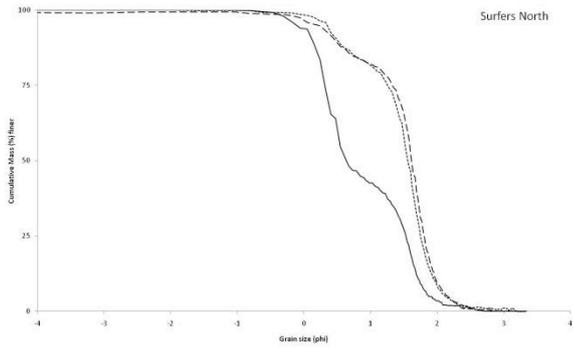
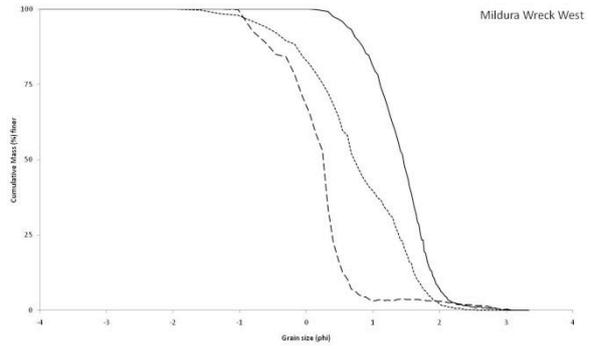
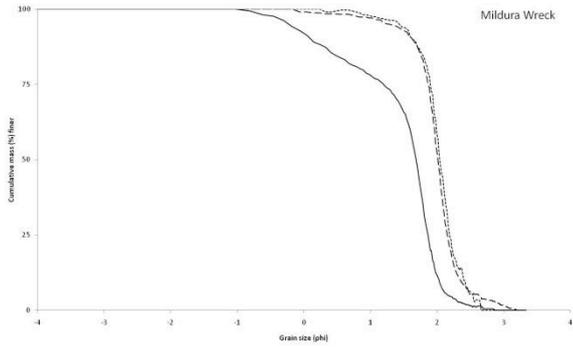
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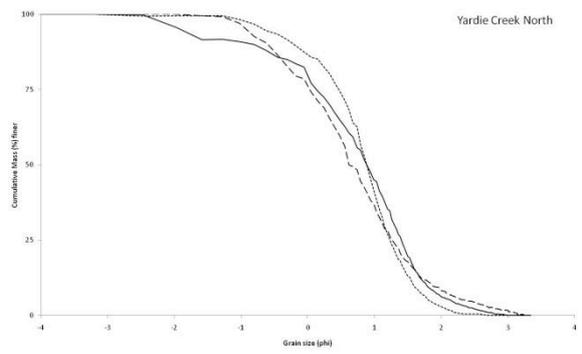
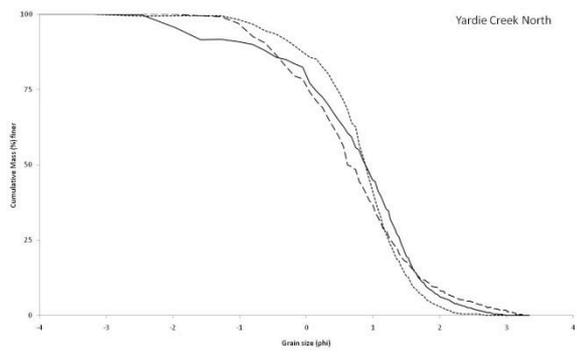
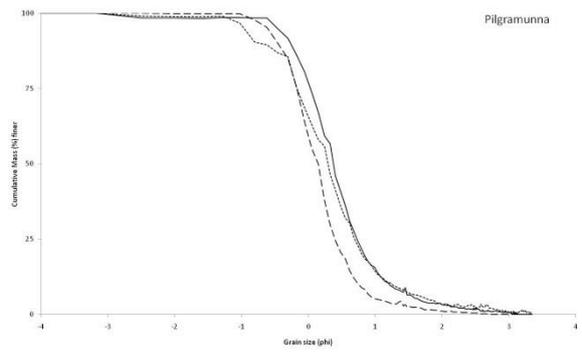
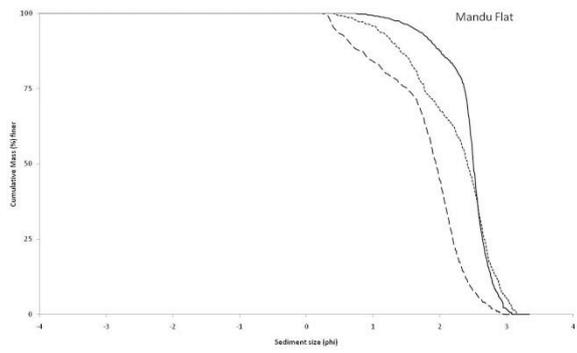
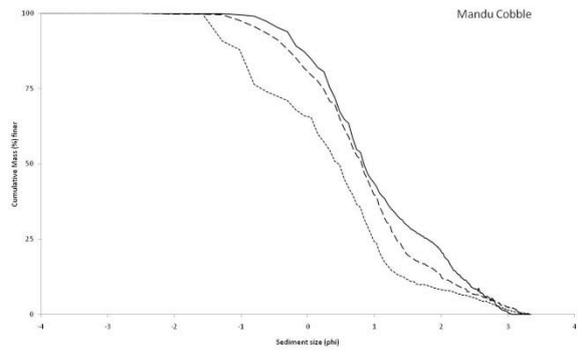
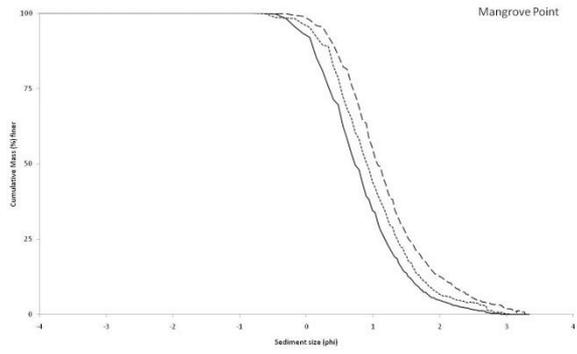
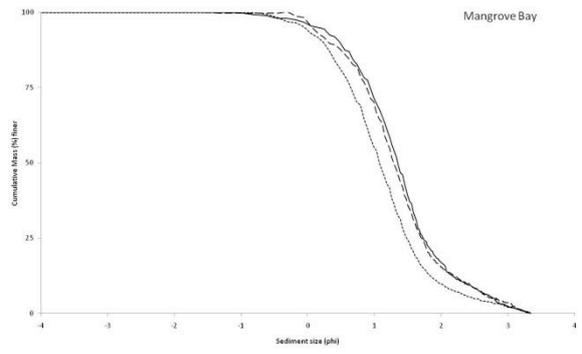
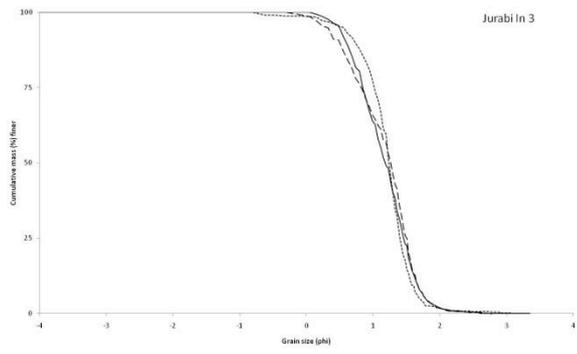


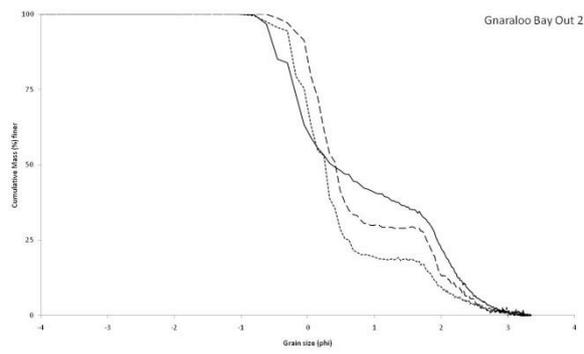
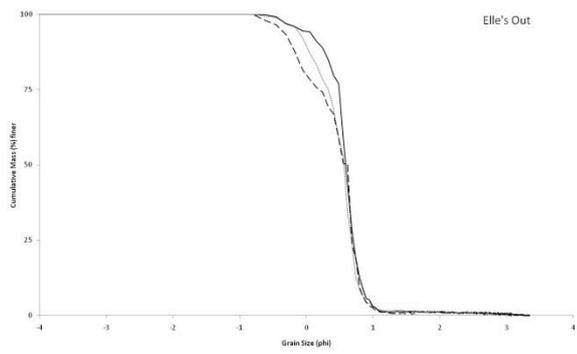
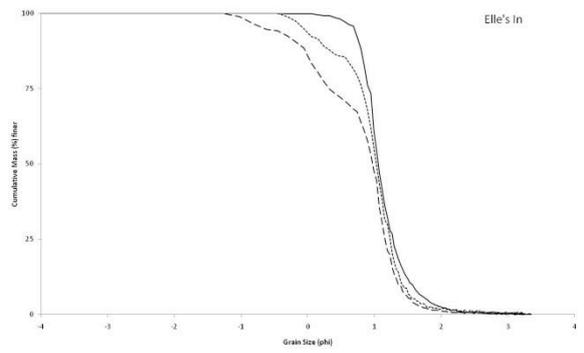
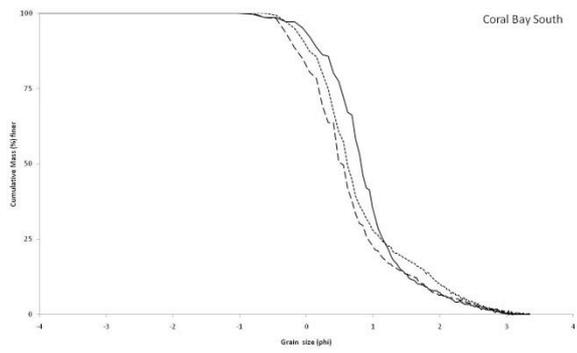
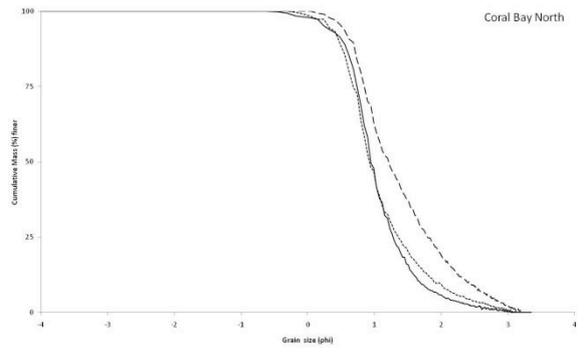
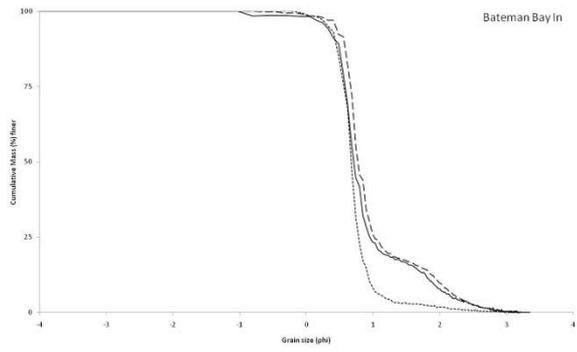
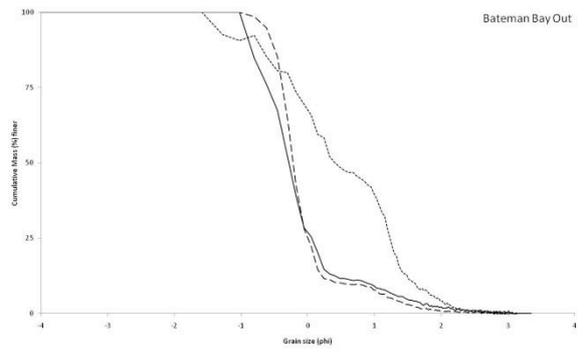
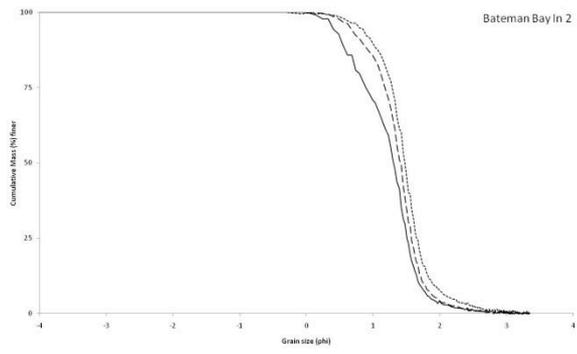
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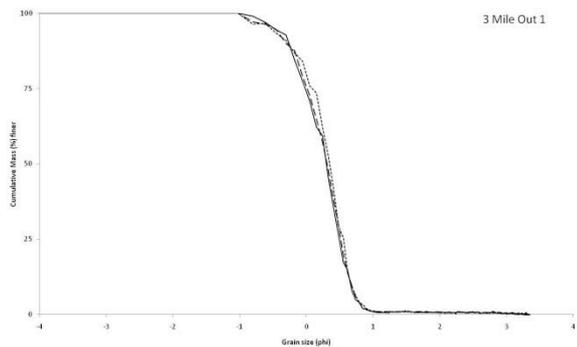
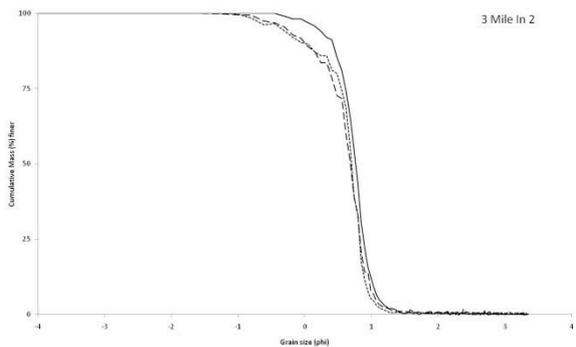
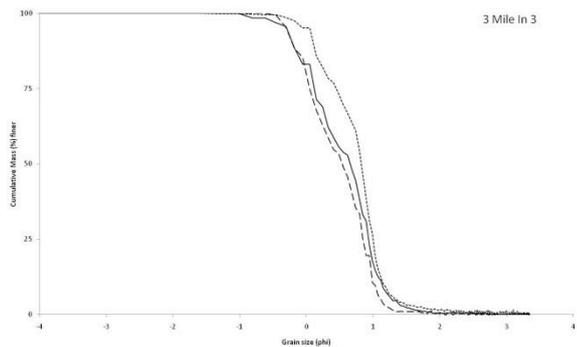
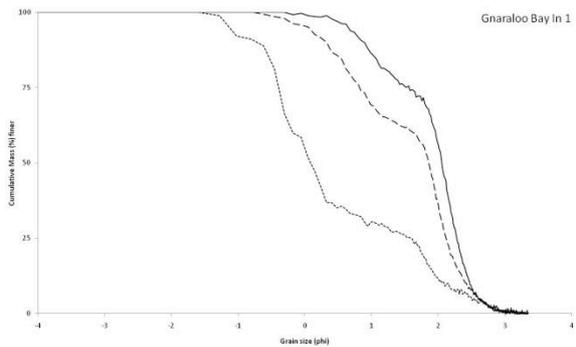
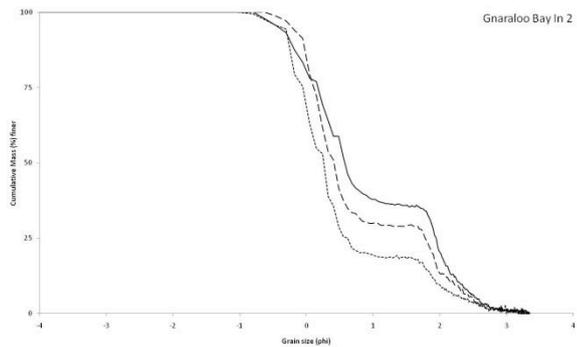


Appendix 5 – Sediment grain size distribution plots.

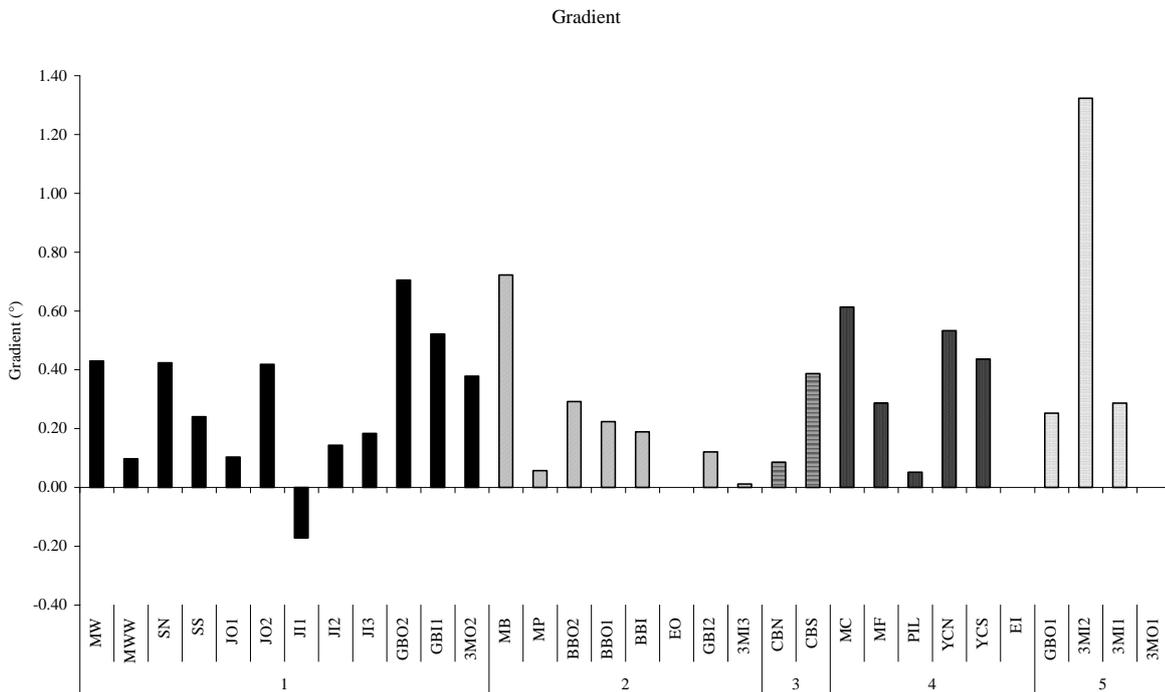
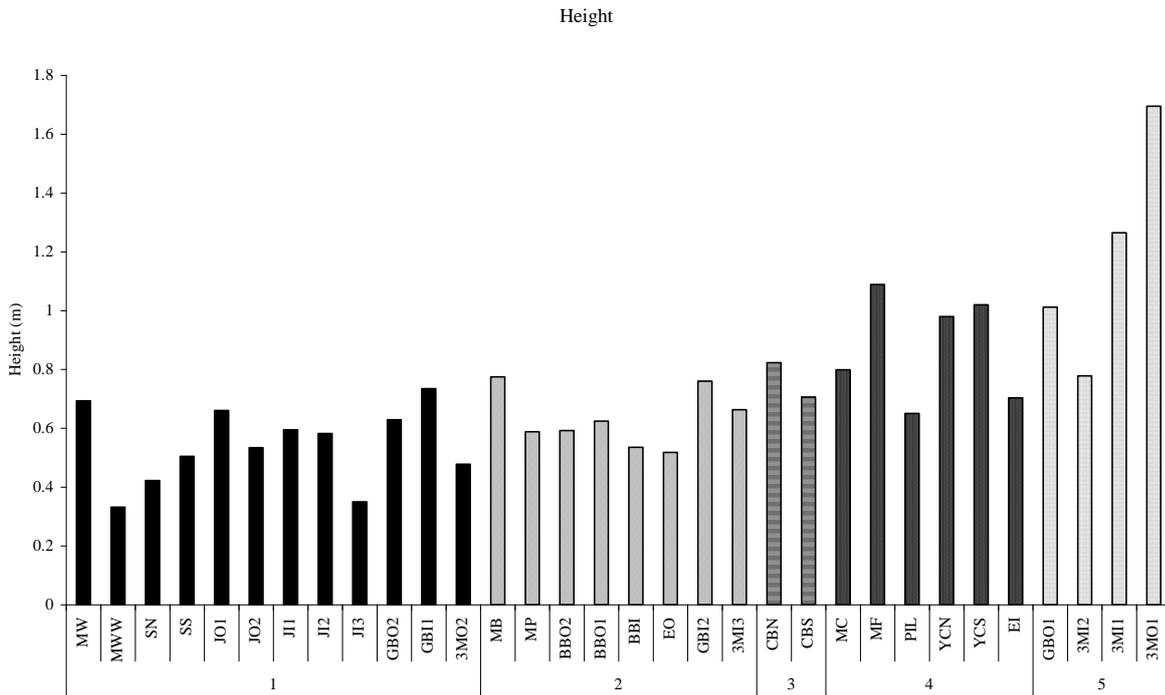




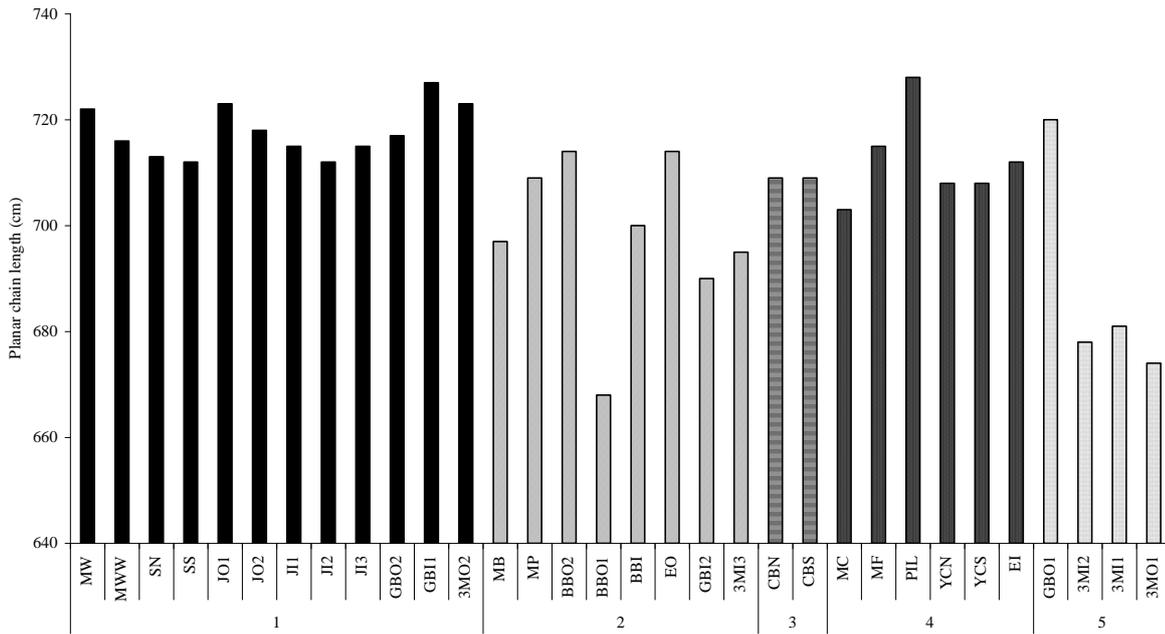




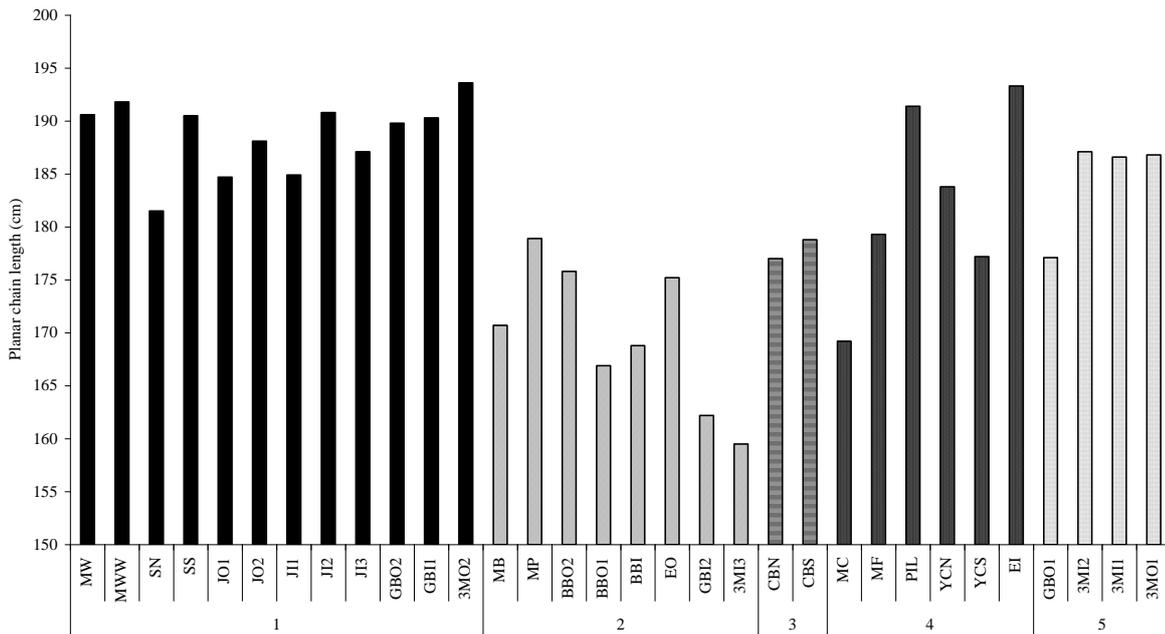
Appendix 6 – Platform variable charts.



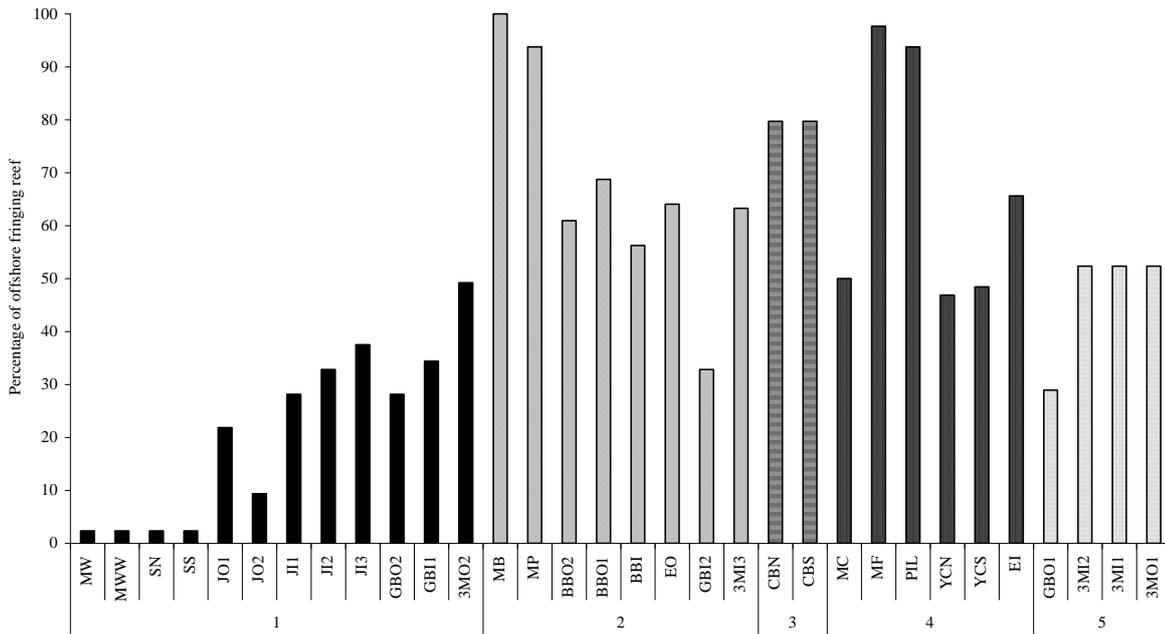
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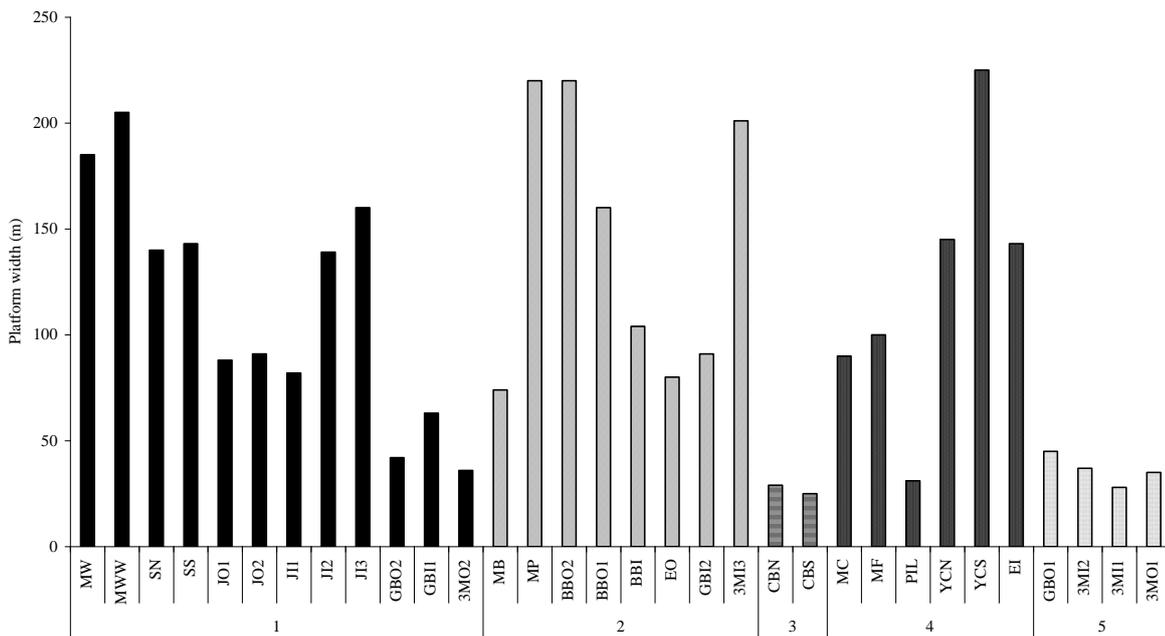
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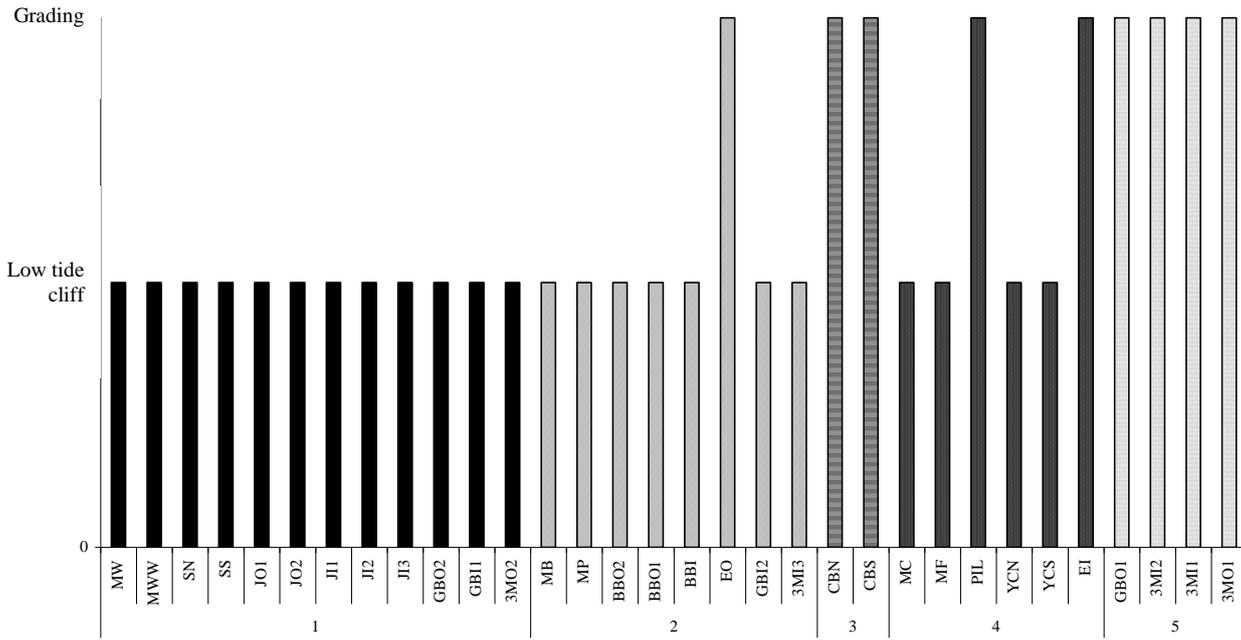
Offshore reef extent



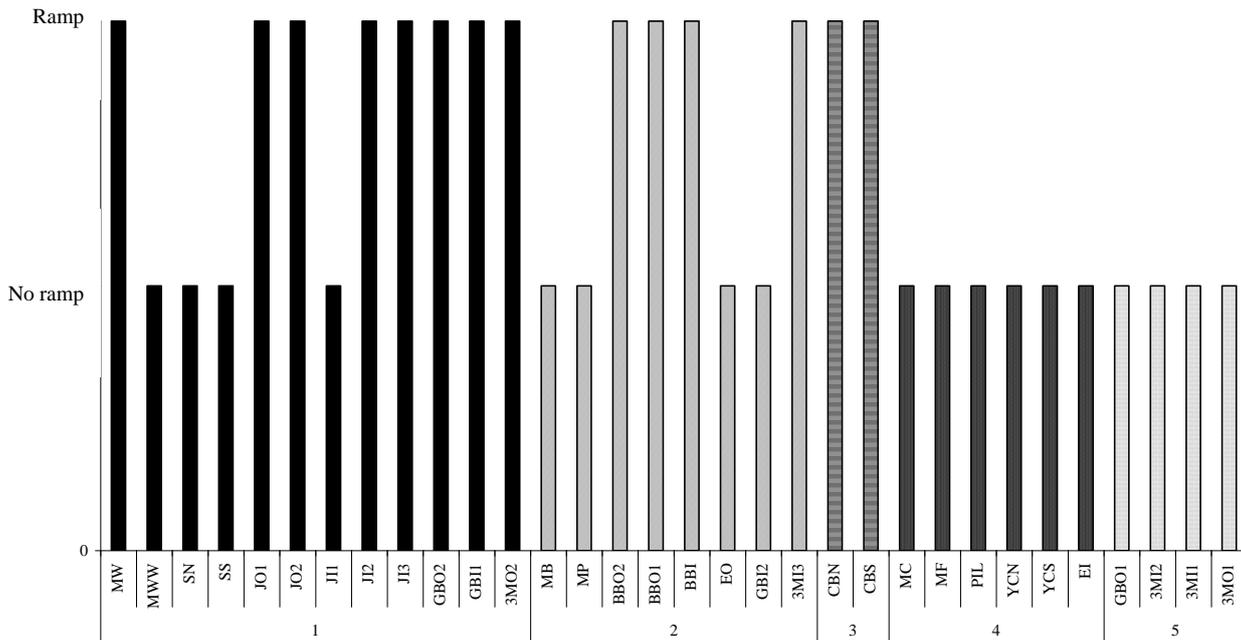
Width



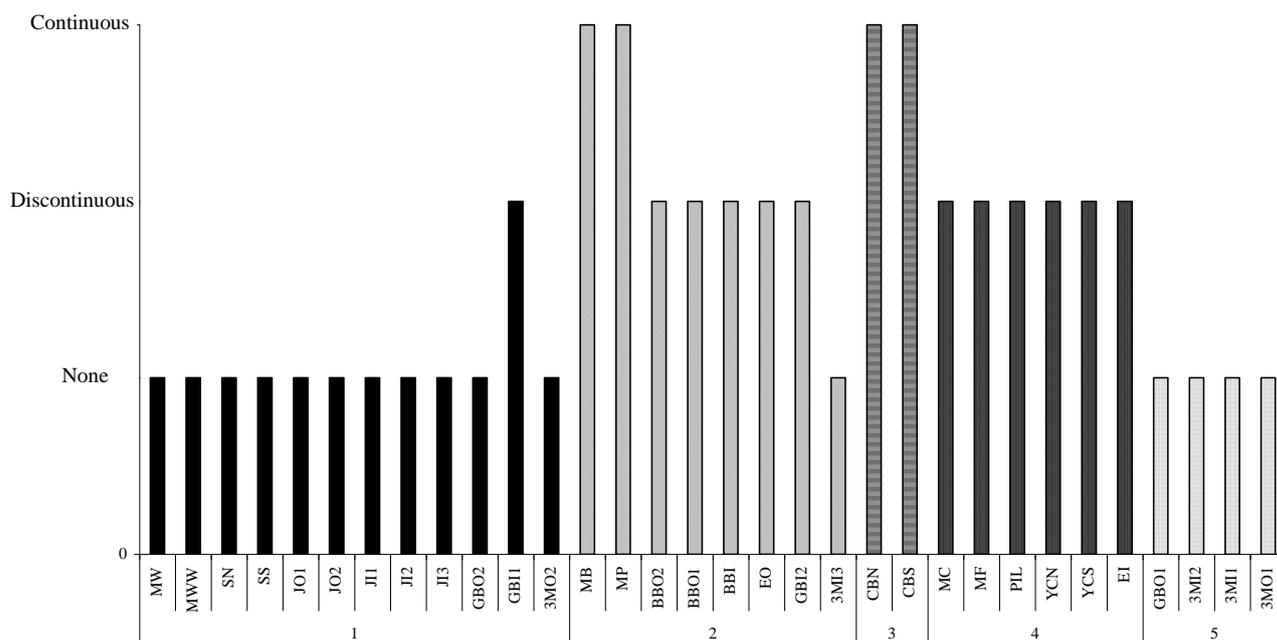
Platform Edge



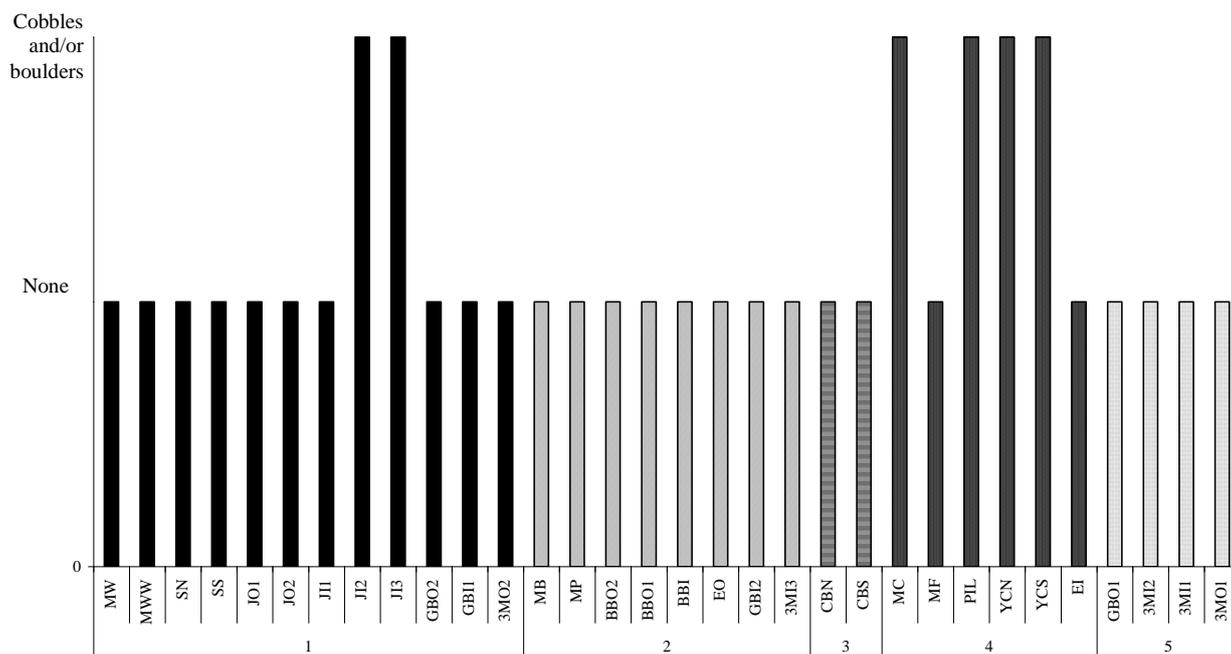
Ramp



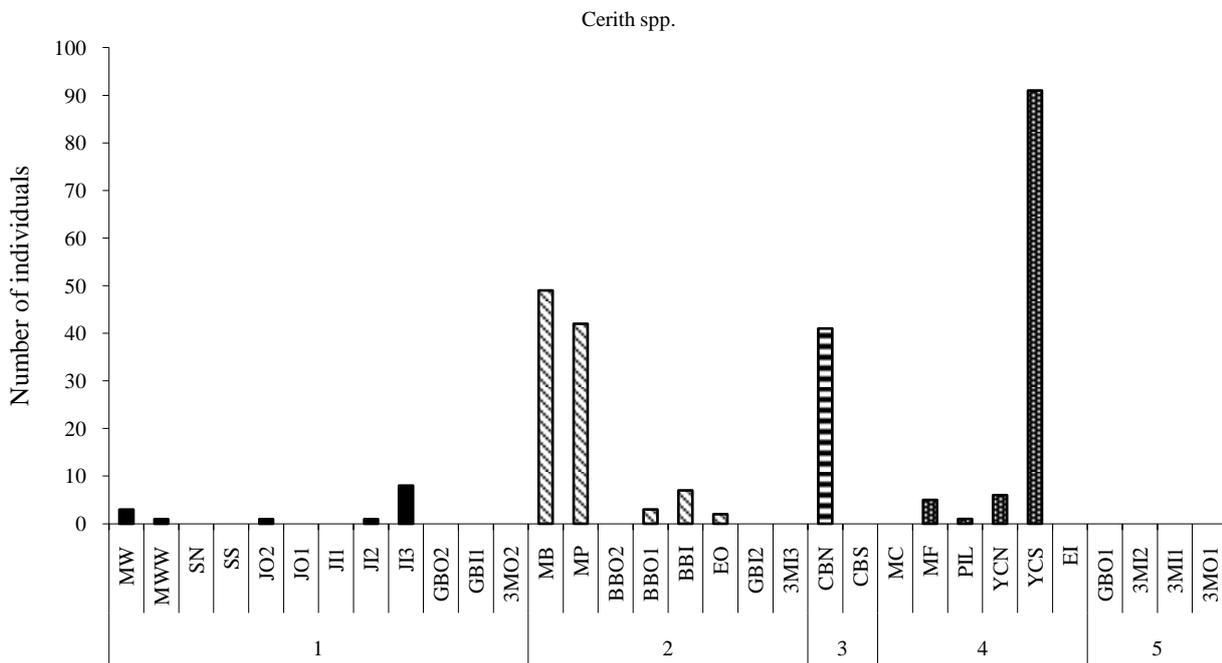
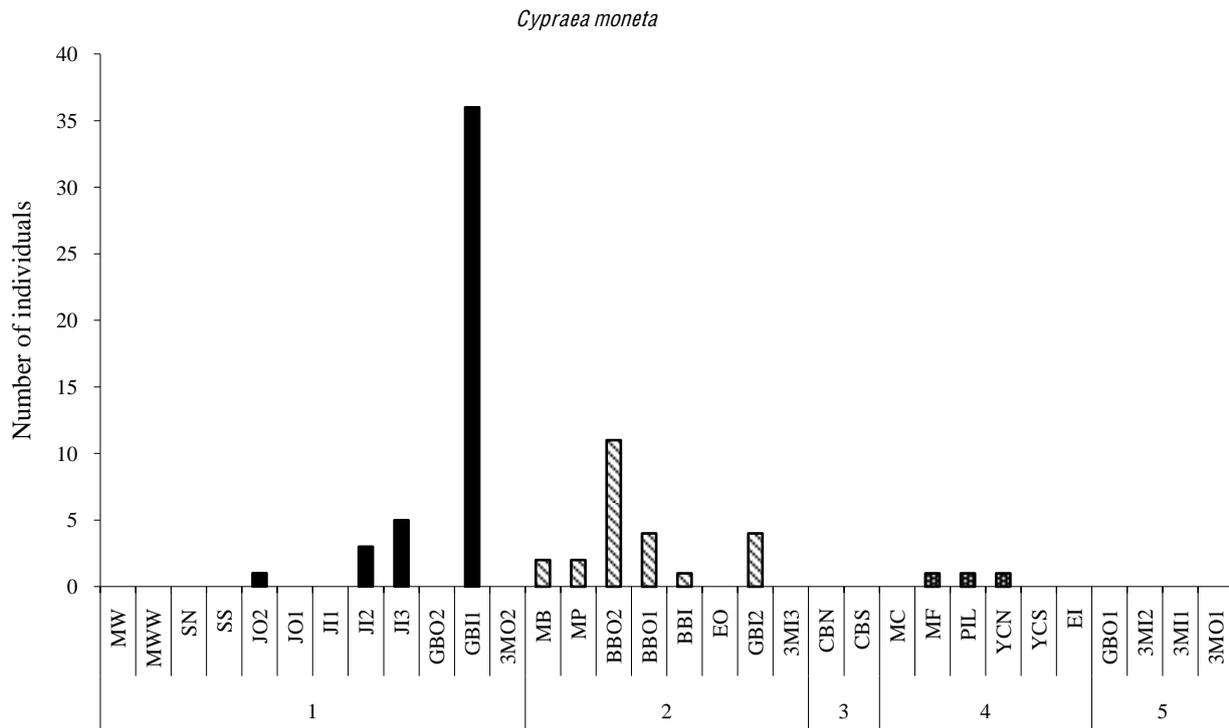
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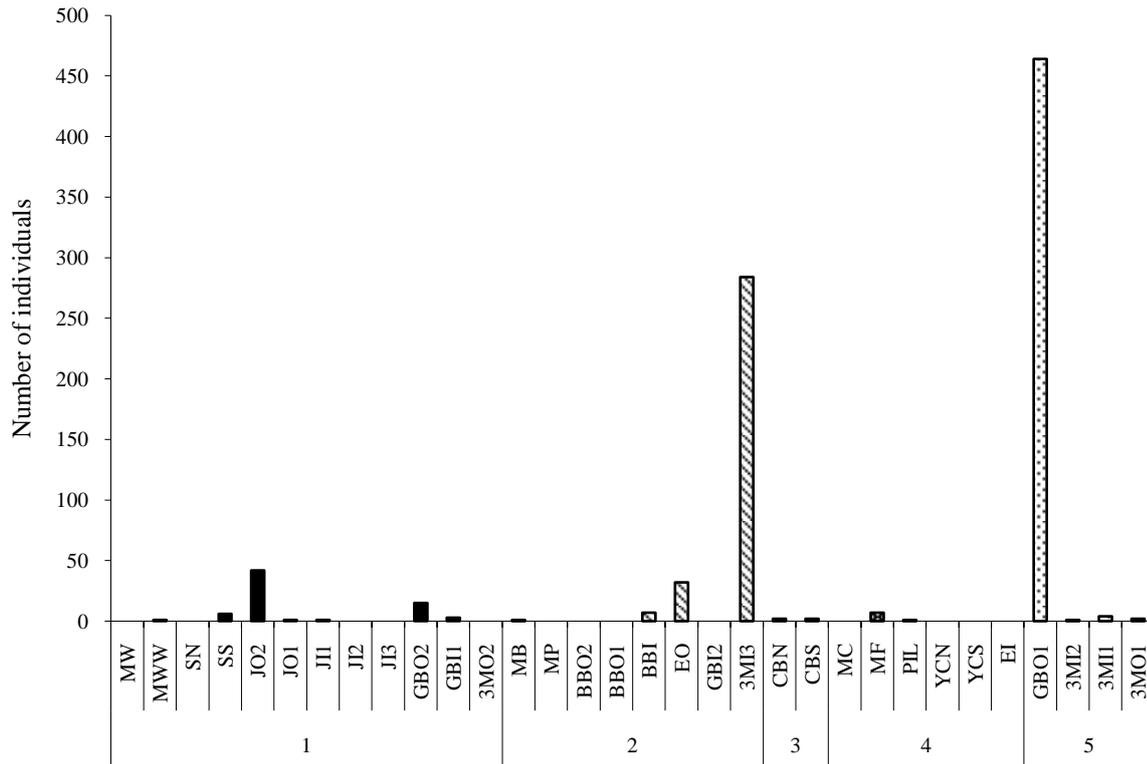
Cobbles or Boulders



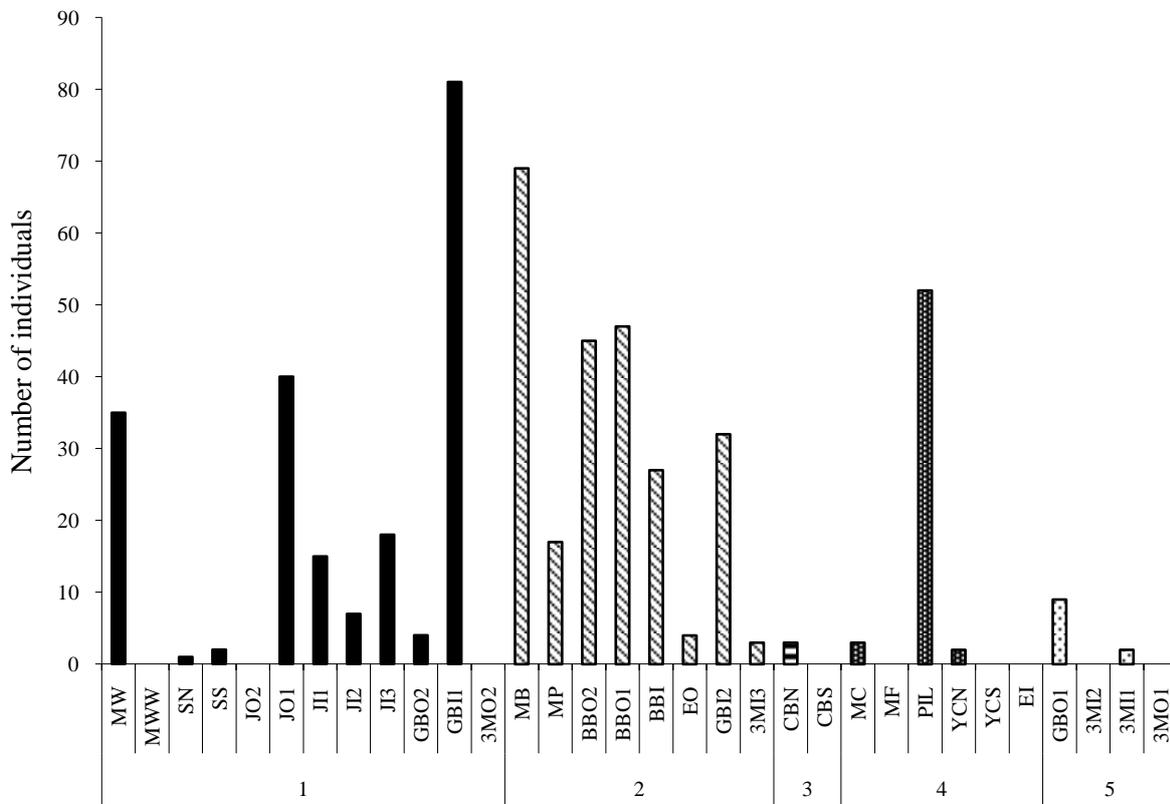
Appendix 7 – Invertebrate assemblage charts.



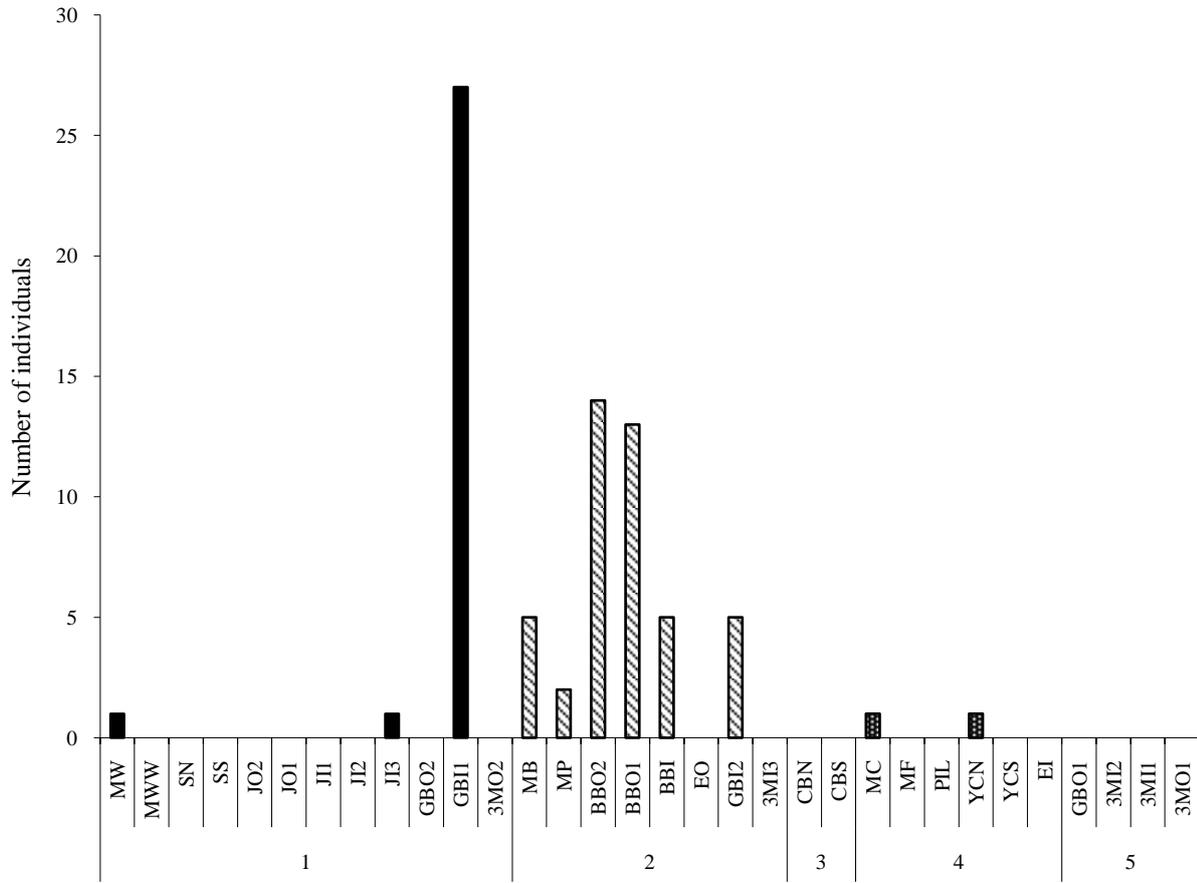
Echinometra mathaei



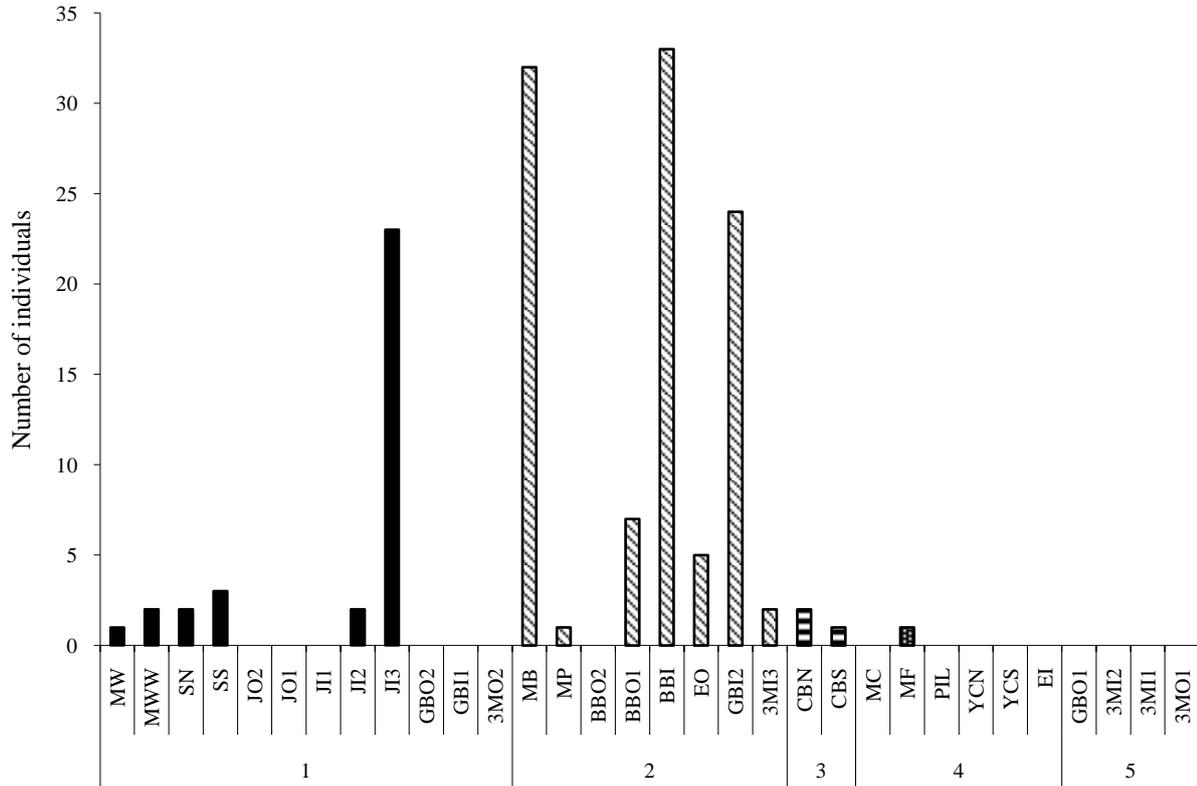
Cronia avellana



Turbo haynesi



Rhinoclavis echinatum_Lamarck_1822



Chapter 9: Comparative methods for the monitoring of sanctuary zones on rocky intertidal platforms at Ningaloo Marine Park

This chapter is the account of a group project conducted as a part of Honours in Zoology by

S.A. Cadee, V.L. Inman, C.G. McHarrie & J.P.A. Taylor

School of Animal Biology, University of Western Australia, Crawley, WA, Australia



Left to right: James Taylor, Victoria Inman, Samantha Cadee, Jane Prince (sitting), Claudia McHarrie, and Anne Brearley. High tide at Jurabi Out 1, 9:33 am, 14 February 2010.

- photo by R. Black

Comparative methods for the monitoring of sanctuary zones on rocky intertidal platforms at Ningaloo Marine Park

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Abstract

For monitoring programs to be successful they require sampling methods that provide accurate data, are cost-effective and repeatable over time. This study tested the application of three sampling methods (systematic grid quadrats, random quadrats and timed search) for use in monitoring macroinvertebrates on intertidal rock platforms in the Jurabi Sanctuary Zone of the Ningaloo Marine Park. Monitoring is required to assess the effectiveness of the sanctuary zones in protecting the invertebrates inhabiting the Ningaloo Marine Park. Eight sites spanning 1.59 kilometres along the intertidal platform were chosen for the study. Four sites lay inside the sanctuary zone (In) and four outside (Out) to allow comparison of the two areas. There was no significant effect of geographical position on the assemblage data. We detected a greater number of species and individuals inside the sanctuary zone than outside with the timed search finding significantly more species than both other methods. The assemblages differed inside and outside the sanctuary zone. This effect was only detected when using the grid and random methods. The assemblage data collected by the grid and random methods did not differ, possibly due to similarities in the number of replicates used and the area covered. The minimum sampling effort required to detect a difference between sites inside and outside of the sanctuary zone was 15 quadrats for both grid and random methods at a minimum of 8 sites. Data collected from 2007 to 2010 found no difference between sites inside and outside of the sanctuary zone. However, this result may be unreliable due to insufficient sampling in previous years.

Keywords: Ningaloo, monitoring, timed search, random quadrats, systematic grid quadrats, rocky intertidal, sampling effort

Introduction

Ningaloo Reef is Australia's longest fringing reef extending for 290 kilometres along the west coast of the Cape Range Peninsula, Western Australia, spanning from 21°40'S to 23°34'S. It is an area of high tourism potential whose remote location has until recently prevented overdevelopment. The reef is exposed to high wave energy and is influenced by cyclonic storms and tsunamis, extreme low tide events, low oxygen conditions resulting from coral spawning, coral bleaching, and predation from gastropods (Cassata & Collins 2008).

The Ningaloo Marine Park is separated into designated sanctuary, recreation, special purpose and general use zones. Sanctuary zones comprise 88,365 hectares (34%), recreation zones comprise 36,460 hectares (14%), special purpose (benthic protection) zones comprise 5,488 hectares (2%), special purpose (shore-based activities) zones comprise 687 hectares (<0.3%), and general use zones comprise 132,343 hectares (50%) of the marine park (MPRA & CALM 2004). Passive recreational activities, nature based tourism, some boating activities, and scientific research may be permitted in sanctuary zones if they are not environmentally detrimental. All extractive activities such as commercial fishing and traditional fishing/hunting are prohibited, as the primary purpose of sanctuary zones is the conservation of marine ecosystems (MPRA & CALM 2004).

The Jurabi Sanctuary Zone is the sixth smallest in size (754 hectares) of the eighteen sanctuary zones in the Ningaloo Marine Park. The area encompassing the intertidal platform is classed as a special purpose (shore-based activities) zone with the sanctuary zone beginning 100 metres off shore. Recreational shore-based fishing, boating, recreational netting, diving, snorkelling and research are permitted in these zones, while activities such as commercial fishing, pearling, collecting, spearfishing and mudcrabbing are prohibited (MPRA & CALM 2004). The exclusion of these activities from management zones allows an opportunity for a greater understanding into the impacts on the ecosystem by comparison with unprotected recreational areas (MPRA & CALM 2004).

Rocky intertidal platforms are particularly vulnerable to human disturbance as they are close to land and easily accessible (Hart *et al.* 2005). Activities such as intensive collecting of sought-after species and trampling of habitat are claimed to lead to

declines in species diversity and abundances (Addessi 1994). The sanctuary zones help to negate these impacts by the prohibition of damaging activities (MPRA & CALM 2004).

Monitoring of sanctuary zones or special purpose zones is important to ensure their effectiveness as a management strategy by observing their condition or changes in condition. Monitoring programs require repeated sampling over time (Murray *et al.* 2006). As such, it is essential that the method used for monitoring provides accurate information about species diversity and abundance while being practical and cost-effective (Miller & Ambrose 2000). Rocky intertidal platforms are known to have high levels of spatial variability even over short distances (Miller & Ambrose 2000). Intertidal zones exposed to moderate wave action are characterised by distinct vertical zones with each zone differing in species composition (Little & Kitching 1996). Consequently, this variability must be taken into account when designing and carrying out monitoring schemes (Murray *et al.* 2006). Furthermore, the intertidal zone is only accessible for sampling when the tide is low, requiring the sampling program to be completed efficiently within a few hours (Murray *et al.* 2006). A number of sampling methods have been tested in previous studies of intertidal platforms, including the use of stratified random sampling, point contact methods, systematic grid sampling, timed searches, belt transects, and random quadrats (Durell *et al.* 2005; Miller & Ambrose 2000; Murray *et al.*, 2006; Raffaelli & Hawkins, 1996). Other studies have also considered sampling at a lower level of taxonomic resolution or using indicator species in order to maximize efficiency, both of which have been found to be effective in rock platform sampling (Bates *et al.* 2007; Guerra-Garcia *et al.* 2006).

This study aimed to test the effectiveness of several sampling methods at monitoring macroinvertebrates with minimal effort on intertidal rock platforms in the Jurabi Sanctuary Zone. Results from this study provide a useful basis for an overall monitoring scheme within the Ningaloo Marine Park. The methods tested were systematic grid quadrats, random quadrats, timed searches and point contacts. The grid method uses systematically placed quadrats throughout the study area. We selected this method due to its effectiveness in covering the spatial variability characteristic of rock platforms (Murray *et al.* 2006). The random quadrat method was chosen primarily to build upon a haphazard quadrat method used previously in intertidal surveys at Ningaloo Marine Park. The haphazard method distributed quadrats throughout a 15 by 50 metre area in

the central part of the platform between the high intertidal and the subtidal sections of the platform (R Black, 2010, pers. comm., 3 February). The random quadrat method selected was advantageous over the haphazard method as it resulted in truly random placement of quadrats and incorporated the edges of the study area (Murray *et al.* 2006). The timed search method involved haphazard searches of the study area within an allotted time frame. Timed searches allow a large area to be searched in a relatively short space of time and are effective in detecting large, relatively uncommon species (Murray *et al.* 2006). In our study, the timed search method measured presence of species and was therefore not easily comparable to the grid and random methods which recorded the numbers of each species. The point contact method scored individuals at specific intervals along a line transect. This method samples across a large area, incorporating spatial variability and is most suitable for estimating the cover of sessile invertebrates (Miller & Ambrose 2000; Murray *et al.* 2006).

Materials and methods

Study sites

Surveys of the macroinvertebrate fauna were conducted at eight sites on intertidal rock platforms along the west coast of the Cape Range Peninsula within the Ningaloo Marine Park, Western Australia. Surveys were conducted from 14 – 19th February 2010, during periods of both morning and afternoon low tide. Four of the sites were within the Jurabi Sanctuary Zone and four sites were outside of the sanctuary zone (Figure 1).

We chose sections of platform with the fewest large rock pools to use as sites. The distance from the shore to the seaward edge of the platform was measured to determine the width of the platform. The width was maintained for 50 metres parallel to the shore.



Figure 1. Position of the eight study sites plotted on Google Earth using GPS coordinates. One centimetre equals 114 metres. Distance between the two furthest sites (In3 to Out2) is 1593 metres.

Field procedures

Before starting each sampling method, we marked out the site with tape measures. We positioned a tape measure 3 metres in from the landward edge of the platform to define the high shore baseline, which was 50 metres long. The end of the platform was defined as the point at which the platform started to slope downwards, termed the low shore baseline, which was marked with a lead rope. We positioned two tape measures perpendicular to the shore to define the edges of the site. The groups of quadrats along the shore were termed rows and the groups of quadrats along the tidal gradient were termed transects. We took GPS (Garmin eTrex) co-ordinates at each corner (Appendix). We sampled six sites at the dawn low tide and two sites (Out3 & In4) at the dusk low tide.

We tested three sampling methods at Jurabi Out1; systematic grid quadrat, random quadrat and point contact. We performed the point contact method by recording species directly below points every 30 centimetres along the A to E transects. After the trial, the point contact method was discontinued as it was time consuming and yielded little data about the site because of the low frequency of contact with organisms. The grid and

random methods were kept and a timed search method was adopted to replace the point contact method.

Systematic grid and random quadrats

For the grid method, a 1 square metre quadrat was placed at the intersection of the rows and transects which formed a grid (Figure 2). Rows 1 to 5 were distributed at regular intervals relative to the width of the platform. The widths of the platforms were 30 metres (In3 & Out3), 40 metres (Out4), 55 metres (In4), 60 metres (Out1), and 64 metres (In1, In2 & Out2). Transects A to E were placed at regular intervals every 12.5 metres along the high shore baseline for all sites. The quadrats furthest from the shore were sampled first due to the rising tide level. The quadrats were systematically searched by two people using glass bottom buckets. A visual search was carried out for sessile species followed by the collection of mobile individuals. Once the quadrat was fully searched, the individuals of each species were counted and recorded on Rite-In-The-Rain water-proof paper. A total of twenty-five quadrats were searched at each site. For the random method, quadrats were placed at random co-ordinates within the site. Each quadrat was searched in the manner mentioned in the grid method.

Timed search

For this method, two people haphazardly searched the sample site for eight 15 minute intervals resulting in a total of two hours searching time. For Out1, the data collected for the two searches were combined at every interval whereas for the remaining sites the data from the two searches remained separate to create two replicates. During each interval, the presence of species was recorded on a slate and unknown species were collected in the glass bottom buckets. Between intervals, the unknown species were identified using the field guide and experienced personnel.

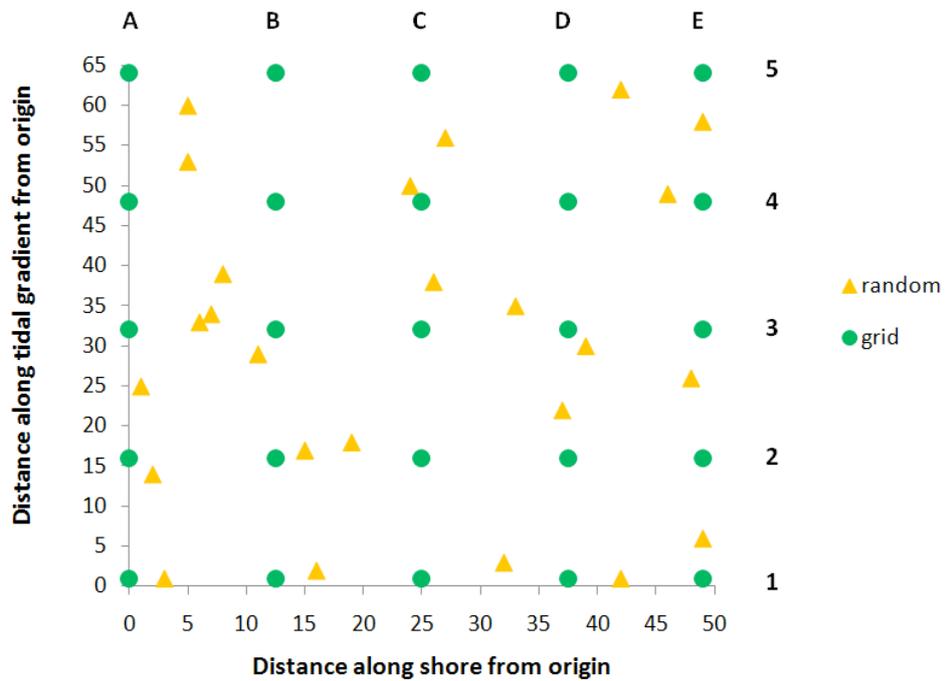


Figure 2. Position of grid and random quadrats within a typical sample site. This example is from Jurabi In1. Green circles indicate grid quadrats and yellow triangles indicate random quadrats. The grid transects started at 0 metres on the high shore baseline (transect A) and were repeated every 12.5m (transects B, C, D and E). The rows started at 0 metres from the shore (row 1) and were repeated until the low shore baseline (row 5). Timed searches took place within the bounds of the search area with no restrictions on the area to be searched at each time interval.

Voucher collection and data collation

For all methods, species that could not be identified in the field were collected in calico bags to be identified at a later time. Collected voucher specimens were preserved in 100% ethanol. The data collected in the field were transcribed into an Excel worksheet at the earliest available opportunity to maintain integrity of the data set. Inconsistencies in the data set were rectified to make it comparable between recorders, sites and dates.

Statistical methods

We used six models for analysis of variance of our data set. Sanctuary was the between sites factor and Method was the within sites factor. Sanctuary, Method, Distance and Date were fixed factors. The first model was used when the replicates considered were quadrats (Table 1). The two orthogonal factors were Sanctuary (In, Out) and Method (Grid, Random). The second model was used when the replicates considered were sites (Table 2). The two orthogonal factors were Sanctuary (In, Out) and Method (Grid,

Random, Timed Search). Timed search was only included when considering species at each site. The third model was used to consider the effect of relative distance within sites using the grid method (Table 3). The two orthogonal factors were Sanctuary (In, Out) and Distance (1, 2, 3, 4, 5). The fourth model was used when the sites were reduced to two (Table 4). The two orthogonal factors were Sanctuary (In, Out) and Method (Grid, Random). There was no Site factor for this model. The fifth model was used to compare data from several years (Table 5). The two orthogonal factors were Sanctuary (In, Out) and Date (2007, 2008, 2009, 2010).

Table 1. Analysis of variance model one used for analyses considering Quadrat as the experimental unit.

Source	df	F
Sanctuary	1	Sanctuary MS/Site(Sanctuary) MS
Site(Sanctuary)	6	Site(Sanctuary) MS/ Method*Site(Sanctuary) MS
Method	1	Method MS/Method*Site(Sanctuary) MS
Method*Sanctuary	1	Method*Sanctuary MS/ Method*Site(Sanctuary) MS
Method*Site(Sanctuary)	6	Quadrat MS
Quadrat	384	

Table 2. Analysis of variance model two used for analyses considering Site as the experimental unit.

Source	df	F
Sanctuary	1	Sanctuary MS/Site(Sanctuary) MS
Site(Sanctuary)	6	Site(Sanctuary) MS/ Method*Site(Sanctuary) MS
Method	1	Method MS/Method*Site(Sanctuary) MS
Method*Sanctuary	1	Method*Sanctuary MS/ Method*Site(Sanctuary) MS
Method*Site(Sanctuary)	6	

Table 3. Analysis of variance model three used for analyses considering Distance as the experimental unit.

Source	df	F
Sanctuary	1	Sanctuary MS/Site(Sanctuary) MS
Site(Sanctuary)	6	Site(Sanctuary) MS/ Distance*Site(Sanctuary) MS
Distance	4	Distance MS/Distance*Site(Sanctuary) MS
Distance*Sanctuary	4	Distance*Sanctuary MS/ Distance*Site(Sanctuary) MS
Distance*Site(Sanctuary)	24	

Table 4. Analysis of variance model four used for analyses where the number of sites was reduced to two.

Source	df	F
Sanctuary	1	Sanctuary MS/Method*Sanctuary MS
Method	1	Method MS/Method*Sanctuary MS
Method*Sanctuary	1	

Table 5. Analysis of variance model five used for analyses considering previous years.

Source	df	F
Sanctuary	1	Sanctuary MS/Site(Sanctuary) MS
Site(Sanctuary)	6	Site(Sanctuary) MS/ Date*Site(Sanctuary) MS
Date	3	Date MS/Date*Site(Sanctuary) MS
Date*Sanctuary	3	Date*Sanctuary MS/ Date*Site(Sanctuary) MS
Date*Site(Sanctuary)	6	

The number of individuals of each species in each quadrat at each site was used to produce rarefaction curves (EstimateS v8.2 2009). This density controlled data set was then used to estimate the number of species that would occur with the lowest total number of individuals (Out1 Random, 126 individuals). These data were then analysed using the second model two-way univariate analysis of variance (JMP v8 2008).

The number of species and the number of individuals were analysed by two-way univariate analysis of variance (ANOVA). The standard errors associated with means generated by JMP are the average of the standard errors of each group. When considering the number of species and individuals within quadrats the first analysis of variance model was used. The second model was used for counts per site. Cochran's C test was carried out on all analyses and any data with heterogeneous variances were transformed by $\log(x+1)$.

The assemblage data and presence/absence data were analysed using multivariate analysis (PRIMER-E v6 2006). The assemblage data were square root transformed for all analyses. Permutational analysis of variance (PERMANOVA) used analysis of variance model two with 4999 permutations. Similarity percentage breakdown (SIMPER) identified the species contributing to dissimilarity using a 50% cut-off to only include species with high contribution. Multidimensional scaling (MDS) plots were generated with principal co-ordinate analysis (PCO) axes fitted and species data were overlaid using Spearman correlation. The Spearman correlation is a non-parametric measure of statistical dependence between two variables. All tests were performed from a Bray-Curtis similarity matrix.

We analysed the effect of distance on the similarity between sites. The similarity values were taken from the Bray-Curtis matrix of the assemblage data. Distances between sites were calculated from the middle of each site to the nearest metre on Google Earth. Correlation was carried out using Excel to determine if there was any significant relationship between distance and similarity. We also analysed the effect of distance from shore on the number of individuals and species by grouping the grid quadrats as rows. This used the two-way univariate analysis of variance model three.

Reduced sample subsets of the assemblage data were generated with twenty, fifteen, ten and five quadrats by removing at random five quadrats for the random method and one transect for the grid method at each site. For each subsequent data set there was an additional five random exclusions. These subsets were analysed by permutational analysis of variance using model one and plotted using principal co-ordinate analysis. Indices of precision were calculated in Excel for the reduced sample subsets by dividing the standard error by the mean dependent variable (number of species or individuals) for each method. The effect of removing rows 1 and 5 from the grid method was observed

by comparing fifteen random quadrats with the fifteen quadrats from the grid. The random quadrats used in this analysis were independent of those in the previous analysis. These data were analysed using permutational analysis of variance model one and plotted using principal co-ordinate analysis. The effect of having fewer replicate sites was analysed by using subsets of the 2010 data that consisted of six, four and two sites. Each subset had one Out and one In site removed at random with additional removals in each subsequent subset. We used model one for analysing six and four sites and model four for two sites. These data were analysed by permutational analysis of variance and plotted using principal co-ordinate analysis. Analysis to determine the minimum number of species required to obtain similar results to the original data set was carried out on the assemblage and presence/absence data using Biota-Environment-Stepwise routine (BVSTEP) in PRIMER-E.

We compared the 2010 data set to data sets from 2007, 2008 and 2009. Previous years had utilised a haphazard quadrat method. In 2010, the grid method data, with rows 1 and 2 excluded, were used to approximate the same search area as previous years. There were fifteen quadrats in the 2010 data set for eight sites (4 In, 4 Out) which were compared with twenty quadrats in the 2007 (1 In, 1 Out), 2008, (2 In, 2 Out), and 2009 (4 In, 2 Out) data sets. The sites designated In1 through Out4 in the 2010 data set are not the same sites used in other years. These assemblage data were analysed in PRIMER-E using permutational analysis of variance model five and principal co-ordinate analysis plots.

Results

There were 3566 individuals belonging to 128 species found in the grid and random methods. The ten most abundant species accounted for 78.7% of the total individuals (Table 6). An additional 39 species not identified in the previous methods were found using the timed search method. In the grid and random methods, 48 of the 128 species were represented by one individual. The number of species found at each site varied from 49 species at Out1 to 79 species at In3 (Table 7). The fewest common species between the three methods occurred at In2 (17.1%) while the greatest amount of common species was at Out4 (32.2%). There were on average more unique species found by the timed search method (18.6 ± 2.3) than both the grid method (8.5 ± 1.3) and the random method (8.3 ± 1.2). There were on average more species per site within the sanctuary zone (73.5 ± 3.3) than outside of the sanctuary zone (55.75 ± 2.9).

Table 6. The ten most abundant species among the 3566 individuals belonging to 128 species found by the grid and random methods

Common name	Scientific name	Number of individuals (In)	Number of individuals (Out)	Percentage of total (%)
Hermit crab	Several species	613	540	32.3
Vermetid gastropod	<i>Serpulorbis sipho</i>	329	103	12.1
Gastropod	<i>Strombus mutabilis</i>	307	44	9.84
Hard Coral	Coral 2mm brown	65	123	5.27
Hard Coral	<i>Porites</i>	94	67	4.5
Giant clam	<i>Tridacna maxima</i>	61	80	3.95
Urchin	<i>Echinometra mathaei</i>	6	115	3.39
Mussel	<i>Septifer bilocularis</i>	11	92	2.89
Cone shell	<i>Conus sponsalis</i>	63	32	2.66
Gastropod	<i>Turbo haynesi</i>	57	4	1.71
Total		1606	1200	78.7

Table 7. Numbers of species found at each site by each method.

Site	Total species	Grid unique species	Random unique species	Timed search unique species	Total common species	% common
In1	64	14	9	17	12	18.8
In2	76	12	13	21	13	17.1
In3	79	11	8	25	17	21.5
In4	75	6	7	25	15	20.0
Out1	49	5	13	7	13	26.5
Out2	62	4	5	25	12	19.4
Out3	53	8	7	13	12	22.6
Out4	59	8	4	16	19	32.2
Average	64.6	8.5	8.3	18.6	14.1	22.3

Rarefaction curves

To determine if there was an effect of density on species richness we corrected the data to 126 individuals using rarefaction. The mean number of species found using the grid method (24.1 ± 0.7) and the random method (24 ± 1.8) were not significantly different (Table 8). Rarefaction curves were generated for the grid method (Figure 3) and the random method (Figure 4).

Table 8. Analysis of variance of the number of species expected per site in 126 individuals for the grid and random methods at sites inside and outside of the sanctuary zone. Cochran's test revealed homogenous variances ($c = 0.6502$, $k = 4$, $df = 3$)

Source	df	MS	F	p
Between sites	[7]			
Sanctuary	1	0.5625	0.0241	0.8817
Site(Sanctuary)	6	23.3125	2.0761	0.1978
Within sites	[8]			
Method	1	0.0625	0.0056	0.9430
Method*Sanctuary	1	5.0625	0.4508	0.5269
Method*Site(Sanctuary)	6	11.2292		

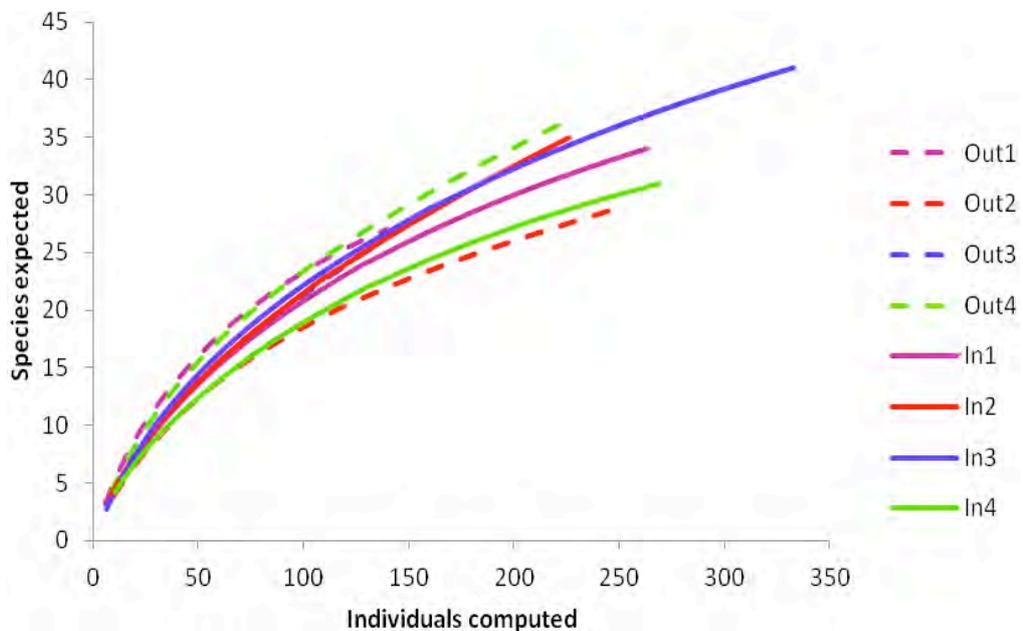


Figure 3. Rarefaction of individuals per site for the grid method at eight sites. The values are computed from the total number of individuals and species at each site.

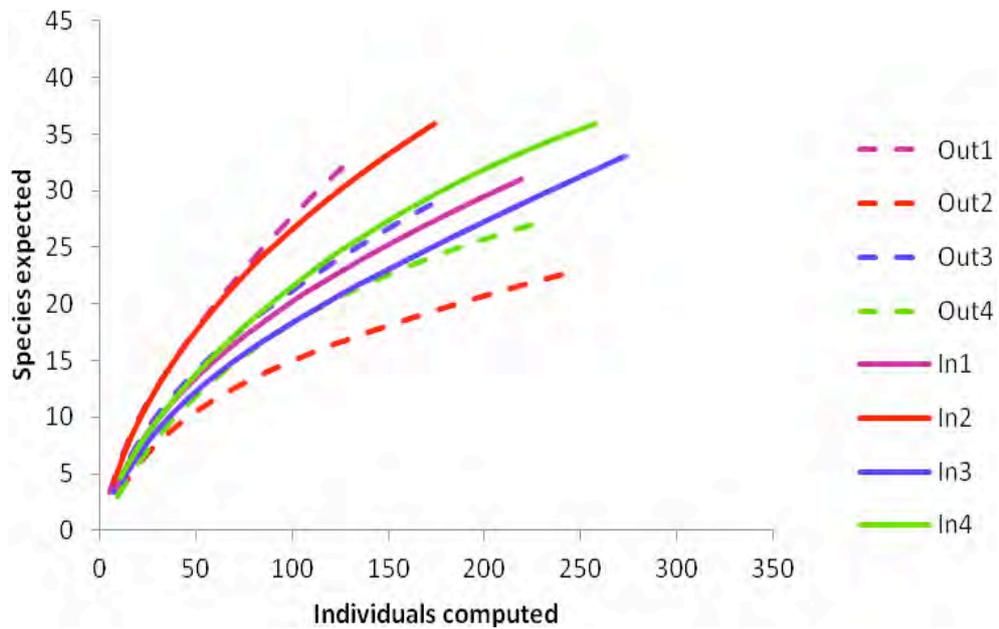


Figure 4. Rarefaction of individuals per site for the random method at eight sites. The values are computed from the total number of individuals and species at each site.

Univariate analysis of number of individuals

Analysis of variance comparing the number of individuals per site for grid and random methods revealed a Method*Sanctuary interaction (Table 9). Outside of the sanctuary zone, the number of individuals found by grid (194 ± 6.0) and random methods (193.75 ± 6.0) did not differ significantly. However, inside the sanctuary zone the number of individuals found by the grid method (272.75 ± 6.0) was higher than the number found using random quadrats (231 ± 6.0) (Figure 5).

Table 9. Analysis of variance of the number of individuals per site for the grid and random methods at sites inside and outside of the sanctuary zone. Cochran's test revealed homogenous variances ($c = 0.3120$, $k = 4$, $df = 3$).

Source	df	MS	F	p
Between sites	[7]			
Sanctuary	1	13456.00	2.896	0.1397
Site(Sanctuary)	6	4645.79	31.793	0.0003
Within sites	[8]			
Method	1	1764.00	12.072	0.0132
Method*Sanctuary	1	1722.25	11.786	0.0139
Method*Site(Sanctuary)	6	146.13		

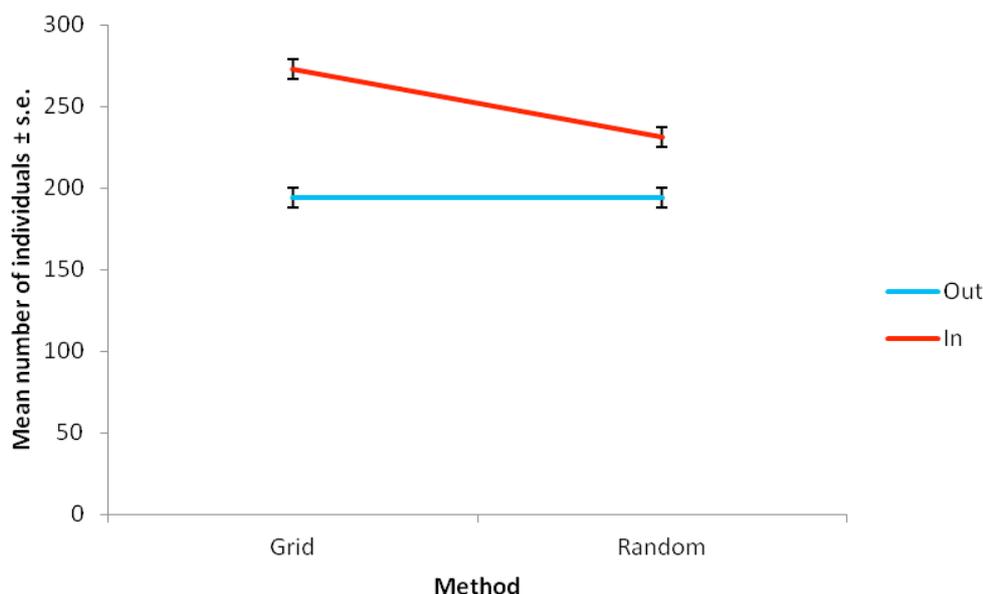


Figure 5. Mean number of individuals per site, with standard errors, found by the grid and random methods for sites inside and outside of the sanctuary zone. Each data point is based on a sample size of four. The analysis of variance for these data is shown in Table 9.

Analysis of variance comparing the number of individuals found per quadrat for the random and grid methods revealed a significant difference in numbers of individuals based on Site(Sanctuary) but not on Method or Sanctuary (Table 10). Out1 had the lowest number of individuals per quadrat (4.2 ± 0.06) while In4 had the highest number (8.5 ± 0.06) (Figure 6).

Table 10. Analysis of variance of the number of individuals per quadrat for the random and grid methods at sites inside and outside of the sanctuary zone. The abundances were transformed using $\log(x+1)$ to homogenise variances. After transformation, Cochran's test revealed homogenous variances ($c = 0.3580$, $k = 4$, $df = 99$).

Source	df	MS	F	p
Between sites	[7]			
Sanctuary	1	1.31924	4.7215	0.0728
Site(Sanctuary)	6	0.27941	7.9522	0.0117
Within sites	[392]			
Method	1	0.00061	0.0174	0.8993
Method*Sanctuary	1	0.02919	0.8308	0.3972
Method*Site(Sanctuary)	6	0.03514	0.2866	0.9432
Quadrat(Method,Site,Sanctuary)	384	0.12259		

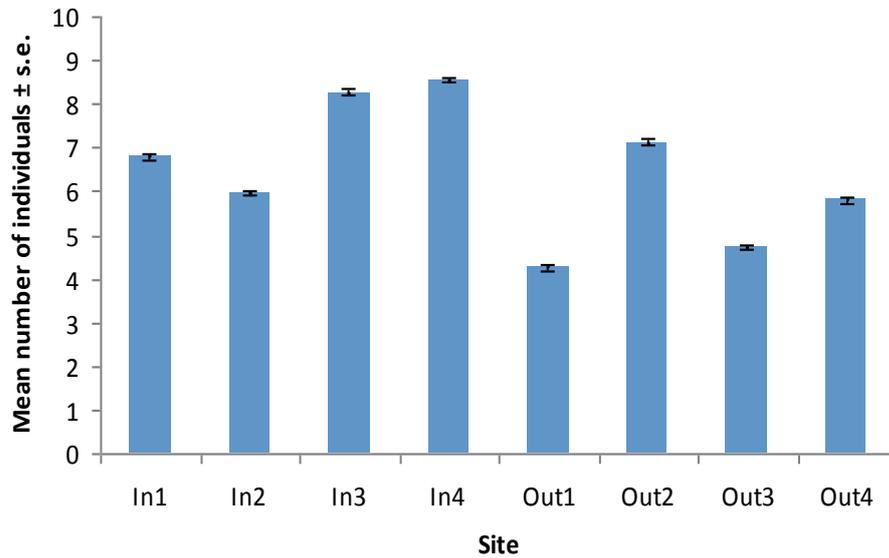


Figure 6. Mean number of individuals per quadrat for the eight sites with standard errors. Each data point is based on a sample size of fifty. The analysis of variance for these data is shown in Table 10.

Univariate analysis of number of species

The mean number of species per site was greater within the sanctuary zone than outside it, as judged by all three methods (Table 11, Figure 7). The mean number of species per site found by each method was significantly different. The number of species found using grid and random methods did not appear to differ significantly. However, the timed search method appeared to find significantly more species than both the grid and random methods.

Table 11. Analysis of variance of the number of species per site for all three methods at sites inside and outside of the sanctuary zone. Cochran's test revealed homogenous variances ($c = 0.4165$, $k = 6$, $df = 3$).

Source	df	MS	F	p
Between sites	[7]			
Sanctuary	1	337.5000	6.6685	0.0416
Site(Sanctuary)	6	50.6111	1.0058	0.4651
Within sites	[16]			
Method	2	421.5420	8.3773	0.0053
Method*Sanctuary	2	21.8750	0.4347	0.6572
Method*Site(Sanctuary)	12	50.3194		

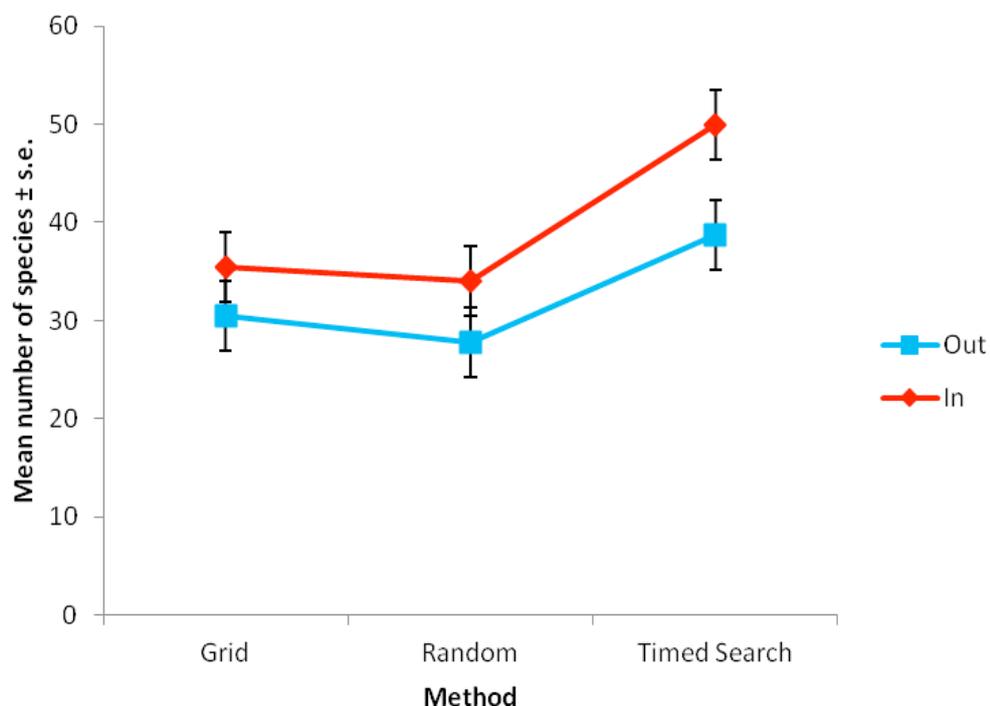


Figure 7. Mean number of species per site for the three methods inside and outside of the sanctuary zone with standard errors. Each data point is based on a sample size of four. The analysis of variance for these data is shown in Table 11.

The number of species per quadrat for the grid and random methods was greater inside the sanctuary zone (4.35 ± 0.16) than outside (3.39 ± 0.16) (Table 12, Figure 8). There was no significant difference based on Site(Sanctuary) or Method.

Table 12. Analysis of variance of the number of species per quadrat for the grid and random methods at sites inside and outside of the sanctuary zone. Cochran's test revealed homogenous variances ($c = 0.3445$, $k = 4$, $df = 99$).

Source	df	MS	F	P
Between sites	[7]			
Sanctuary	1	92.16000	18.738	0.0049
Site(Sanctuary)	6	4.91833	0.719	0.6508
Within sites	[392]			
Method	1	4.84000	0.707	0.4326
Method*Sanctuary	1	0.25000	0.037	0.8547
Method*Site(Sanctuary)	6	6.84500	1.576	0.1528
Quadrat(Method,Site,Sanctuary)	384	4.34354		

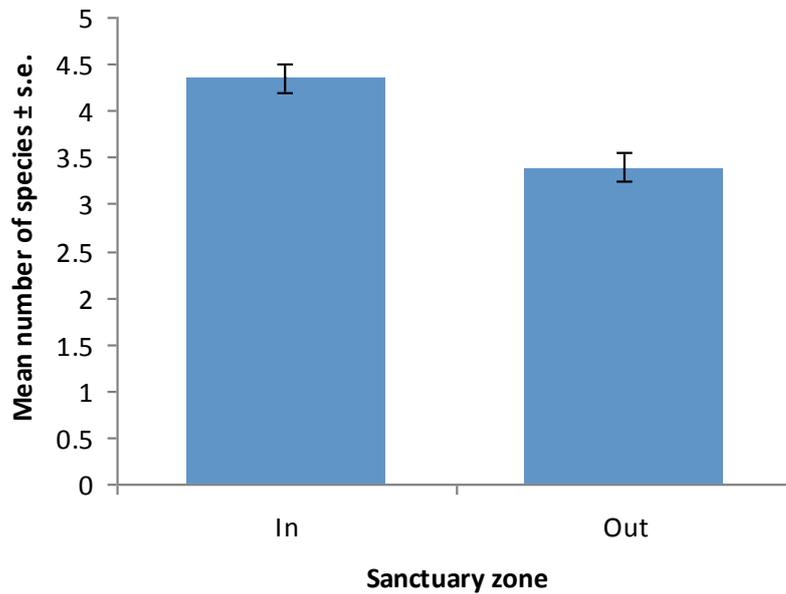


Figure 8. Mean number of species per quadrat found inside and outside of the sanctuary zone with standard errors. Each data point is based on a sample size of two hundred. The analysis of variance for these data is shown in Table 6.

Multivariate analysis

Permutational analysis of variance revealed a difference in the assemblage data based on Site(Sanctuary) and Sanctuary (Table 13, Figure 9). This analysis makes use of the quantitative estimates of abundances of each species using only grid and random methods. Tight clustering of each method is apparent, as is distinct separation between sites inside and outside of the sanctuary zone. There was 53.36% average dissimilarity between levels of Sanctuary with the main sources of dissimilarity being that of *S. mutabilis* (6.2%), *S. sipho* (5.95%), and hermit crabs (4.96%) which were more abundant within the sanctuary zone, and *E. mathaei* (3.6%), and *S. bilocularis* (3.6%) which were more abundant outside of the sanctuary zone. All other species contributed less than 3% to the dissimilarity. It should be noted that *Cerithium echinatum* is the one species with a strong correlation (>0.7) which was not amongst the ten most abundant species.

Table 13. Permutational analysis of variance of the assemblage data at each site for the grid and random method at sites inside and outside of the sanctuary zone.

Source	df	MS	Pseudo -F	p	Unique permutations
Between sites	[7]				
Sanctuary	1	4216.00	2.753	0.0294	35
Site(Sanctuary)	6	1531.60	2.310	0.0002	4968
Within sites	[8]				
Method	1	978.42	1.476	0.1862	4966
Method*Sanctuary	1	600.75	0.906	0.5490	4963
Method*Site(Sanctuary)	6	663.04			

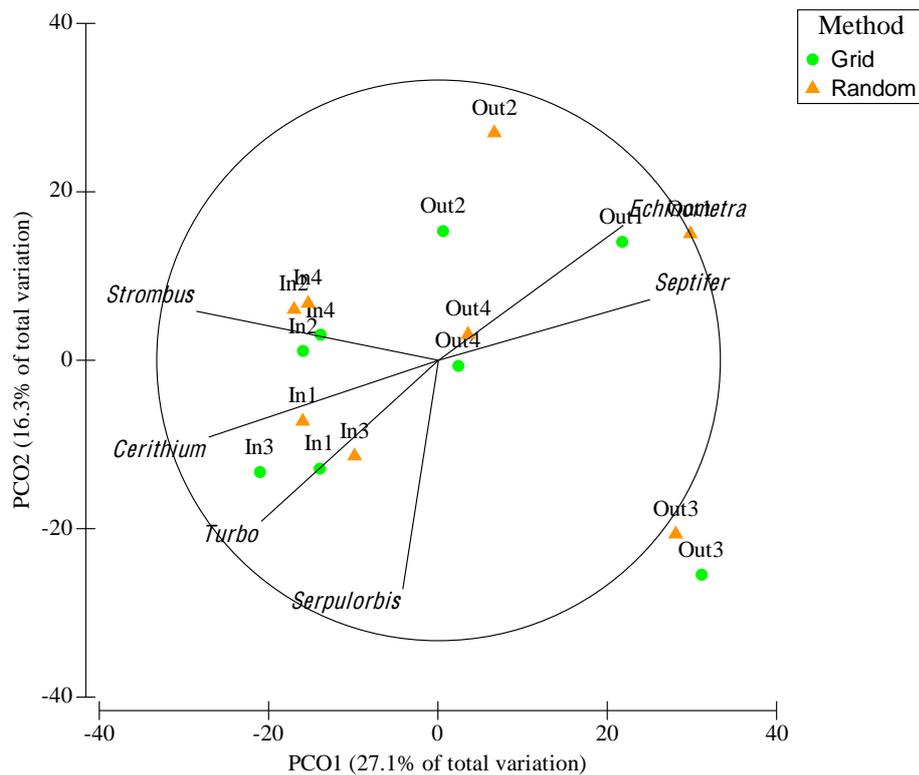


Figure 9. Multidimensional scaling by principal co-ordinate analysis of the assemblage data for each site for the grid and random methods plotted on the first two principal co-ordinate axes. The grid method is indicated with a green circle and random method is indicated with a yellow triangle. Lines indicate the correlation (> 0.7) of species indicated with the PCO axes, with the overlaid circle representing a correlation of one. The six species indicated are *Echinometra mathaei*, *Septifer bilocularis*, *Serpularbis siphos*, *Turbo haynesi*, *Cerithium echinatum*, and *Strombus mutabilis*. The permutational analysis of variance for these data is shown in Table 13.

The following analysis ignores the quantitative abundances and reduces the quality of the data to presence/absence, allowing the inclusion of the timed search data. This analysis allows us to determine if the effect of Sanctuary and Method remain when reducing the data quality. Permutational analysis of variance revealed a significant effect of Method, Site and Sanctuary (Table 14, Figure 10). An independent analysis of the timed search data did not reveal a significant difference between the sites based on Sanctuary. Pair-wise tests were performed on the methods and found no significant difference between grid and random methods ($p = 0.14$), a significant difference between grid and timed search methods ($p = 0.0174$) and a significant difference between random and timed search methods ($p = 0.0198$). There was 52.36% average dissimilarity between sites inside and outside of the sanctuary zone with the main sources of dissimilarity being that of *Morula uva* (1.82%), which occurred more frequently within the sanctuary zone, and Polychaete sedentary (1.8%), *T. haynesi* (1.78%), *C. echinatum* (1.68%), *Balanoglossus* (1.53%), and Polychaete errant (1.5%), which occurred more frequently outside of the sanctuary zone. All other species contributed less than 1.5% to the dissimilarity.

There was 51.96% average dissimilarity between the grid and timed search methods with the main sources being that of soft coral feathery (1.91%), flat worm brown (1.78%), *Holothuria atra* (1.71%), Holothurian brown (1.58%), Octopus (1.52%), and Chiton white (1.51%), which occurred more frequently within the timed search method. All other species contributed less than 1.5% to the dissimilarity. There was 51.83% average dissimilarity between the random and timed search methods with the main sources being that of soft coral feathery (1.98%), flat worm brown (1.83%), *H. atra* (1.78%), *Palythoa densa* (1.57%), and Octopus (1.56%), which all occurred more frequently within the timed search method. All other species contributed less than 1.5% to the dissimilarity.

Table 14. Permutational analysis of variance on the presence or absence of each species at sites inside and outside of the sanctuary zone.

Source	df	MS	Pseudo -F	p	Unique permutations
Between sites	[7]				
Sanctuary	1	4131.1	3.2619	0.0272	35
Site(Sanctuary)	6	1266.5	1.3477	0.0348	4964
Within sites	[16]				
Method	2	2455.3	2.6129	0.0004	4976
Method*Sanctuary	2	747.8	0.7957	0.7478	4977
Method*Site(Sanctuary)	12	939.7			

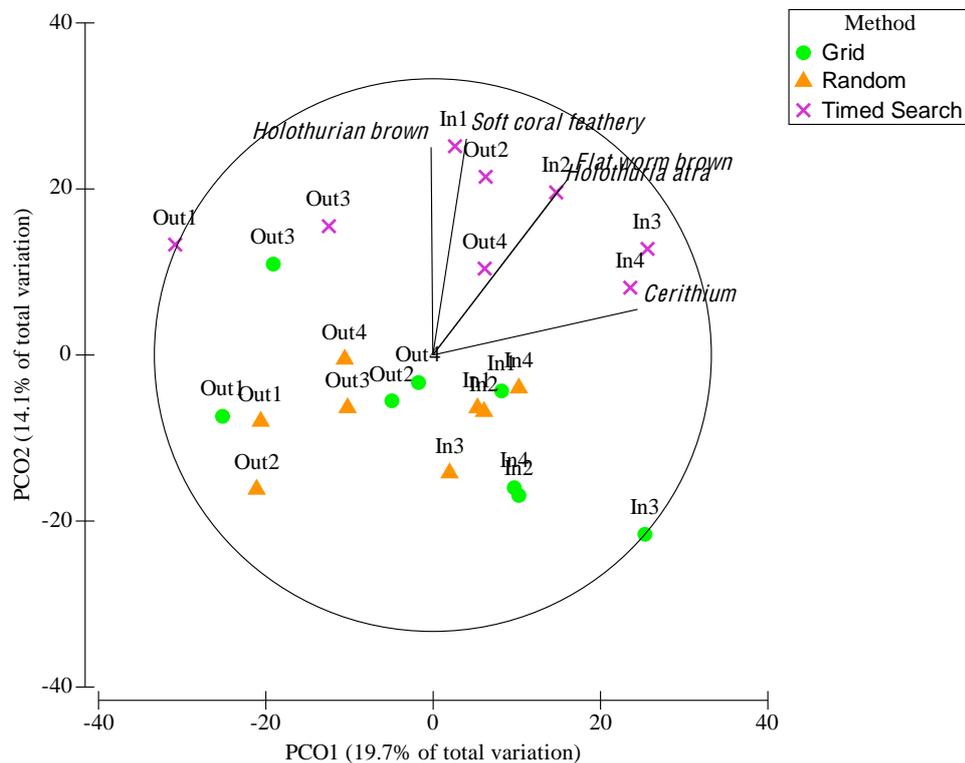


Figure 10. Multidimensional scaling by principal co-ordinate analysis of presence/absence data for each site for all methods plotted on the first two principal co-ordinate axes. The grid method is indicated with a green circle, the random method is indicated with a yellow triangle and the timed search method is indicated with a pink cross. Lines indicate the correlation (> 0.7) of species indicated with the PCO axes, with the overlaid circle representing a correlation of one. The five species indicated are Holothurian brown, soft coral feathery, flat worm brown, *Holothuria atra* and *Cerithium echinatum*. The permutational analysis of variance for these data is shown in Table 14.

Spatial variability

Spatial variability was analysed both within sites and between sites. The variability within sites was analysed by examining the number of individuals (Table 15, Figure 11) and number of species (Table 16, Figure 12) per quadrat, against the distance from shore. Despite the Distance*Site(Sanctuary) interaction for both the number of individuals and species, there was still a significant effect of Distance. There was a greater number of individuals and species in rows 3 to 5 which differed from row 1 as indicated by Tukey's test.

Table 15. Analysis of variance of the number of individuals per quadrat in the grid method by distance from shore at sites inside and outside of the sanctuary zone.

Source	df	MS	F	P
Between sites	[7]			
Sanctuary	1	496.1250	5.3590	0.0599
Site(Sanctuary)	6	92.6317	0.8244	0.5623
Within sites	[192]			
Distance	4	662.5330	5.8965	0.0019
Distance*Sanctuary	4	193.5620	1.7227	0.1779
Distance*Site(Sanctuary)	24	112.3610	2.6564	0.0002
Quadrat(Distance,Site,Sanctuary)	160	42.2975		

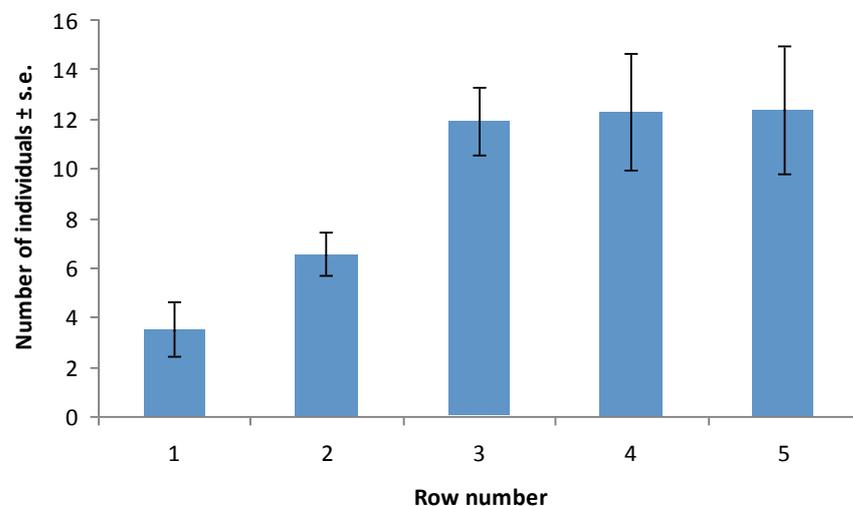


Figure 11. Mean number of individuals per row with standard errors. Standard errors are calculated from the variation of the mean from the site average. Each data point is based on a sample size of forty. The analysis of variance for these data is shown in Table 15.

Table 16. Analysis of variance of the number of species per quadrat in the grid method by distance from shore at sites inside and outside of the sanctuary zone.

Source	df	MS	F	P
Between sites	7			
Sanctuary	1	51.0050	4.9272	0.0682
Site(Sanctuary)	6	10.3517	1.1971	0.3415
Within sites	192			
Distance	4	53.7325	6.2136	0.0014
Distance*Sanctuary	4	9.14250	1.0572	0.3990
Distance*Site(Sanctuary)	24	8.64750	2.5029	0.0004
Quadrat(Distance,Site,Sanctuary)	160	3.455		

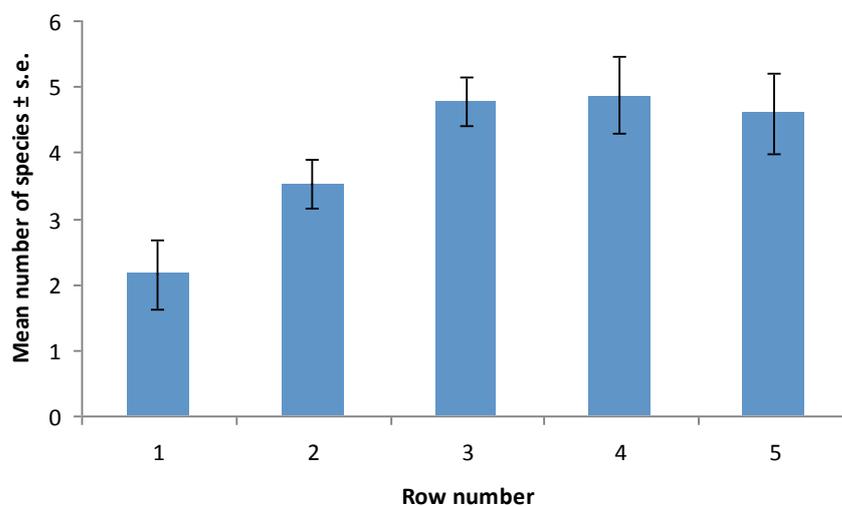


Figure 12. Mean number of species per row with standard errors. Standard errors are calculated from the variation of the mean from the site average. Each data point is based on a sample size of forty. The analysis of variance for these data is shown in Table 16.

To ensure the geographic position of sites was not confounding the data, we determined the effect of distance between sites on the similarity of sites (Figure 13). The correlation coefficient of the relationship between these variables found no significant correlation for the grid method ($p = 0.0624$) or random method ($p = 0.12$). These findings indicate that the geographic position of the sites does not affect community composition.

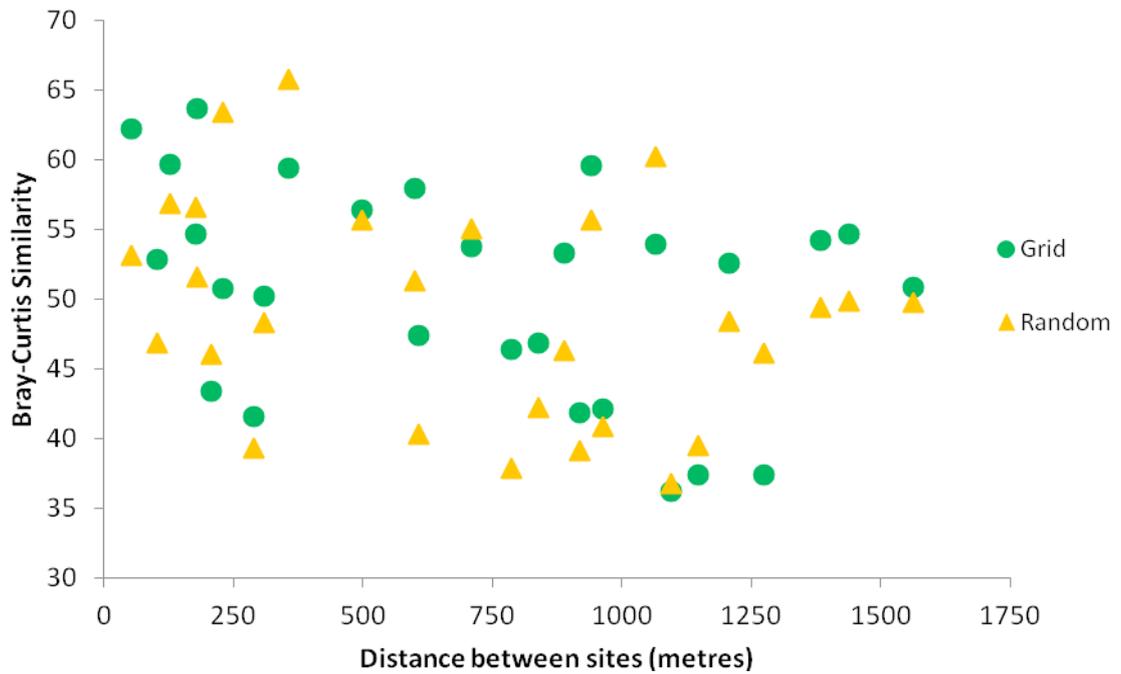


Figure 13. Spatial variation between sites. Distances were calculated from the middle of each site to the nearest metre, on Google Earth. Green circles indicate the grid method and yellow triangles indicate the random method. Each method is based on a sample size of twenty eight.

Effects of reduced sampling effort

We looked at the most efficient way of minimising sampling effort without loss of accuracy. Simulations were conducted using reduced numbers of quadrats, sites, and the number of species sampled.

We were interested in verifying whether the timed search method identified the majority of the species at the sites sampled. A species accumulation curve was plotted for the timed search data (Figure 14). The timed search for In4 found the most species and Out4 found the least species. None of the species accumulation curves appear to reach an asymptote, meaning more species would be identified with more sampling effort.

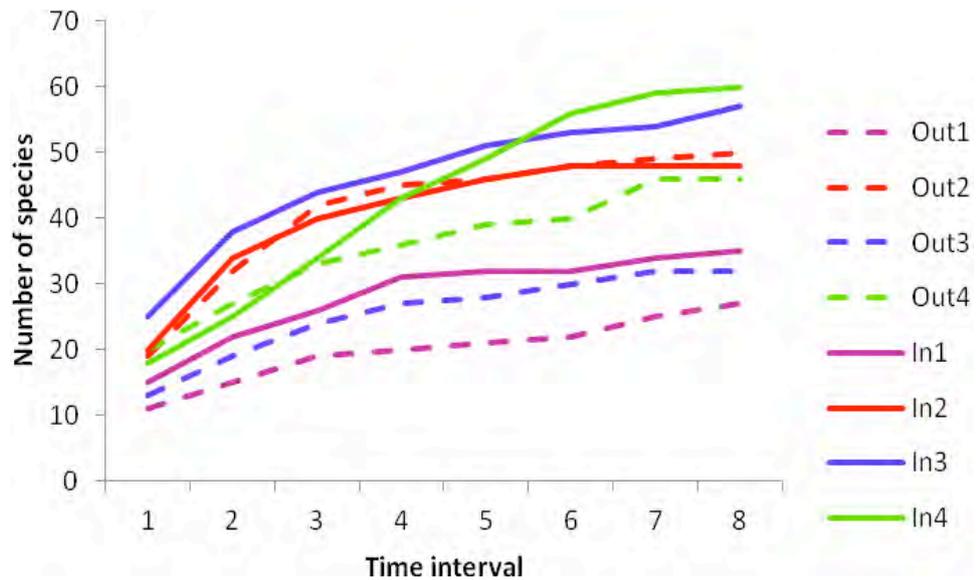


Figure 14. Timed search species accumulation curves for the eight sites. Each time interval is of 15 minutes duration. Out1 is plotted from data for one timed search. Out2 through In4 are plotted from merged data from two timed searches.

We were interested in the effect of reducing the number of quadrats used in the grid and random methods on the assemblage data (Table 17, Figures 15-18). For all reductions, Site(Sanctuary) remained a significant effect. The Sanctuary effect remained significant for twenty quadrats and fifteen quadrats but was not significant when using ten or five quadrats. This means that fifteen quadrats is the minimum number of samples needed to retain the same pattern as sampling twenty five quadrats.

Table 17. Probabilities of the assemblage data based on simulations using fewer quadrats. The reduction in quadrats is a result of the removal of random transects from the grid method, and five random quadrats for each reduction. The degrees of freedom for the model are the same as Table 13.

Source	p (25)	p (20)	p (15)	p (10)	p (5)
Between sites					
Sanctuary	0.0294	0.0256	0.0286	0.0648	0.0868
Site(Sanctuary)	0.0002	0.0002	0.0002	0.0004	0.0044
Within sites					
Method	0.1862	0.2976	0.2308	0.2836	0.1246
Method*Sanctuary	0.5490	0.7308	0.8540	0.8624	0.5678

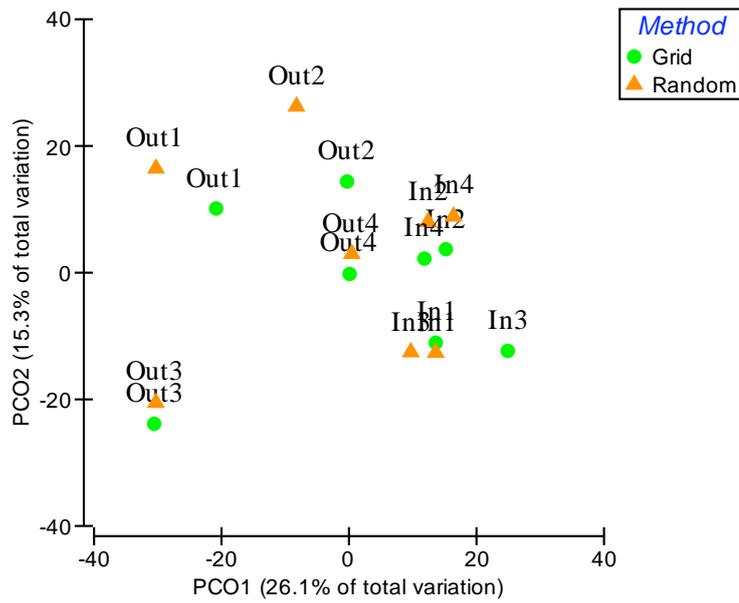


Figure 15. Multidimensional scaling by principal co-ordinate analysis of the assemblage data for each site for the grid and random methods using twenty quadrats plotted on the first two principal co-ordinate axes. The grid method is indicated by a green circle and the random method is indicated by a yellow triangle. The permutational analysis of variance for these data is shown in Table 17.

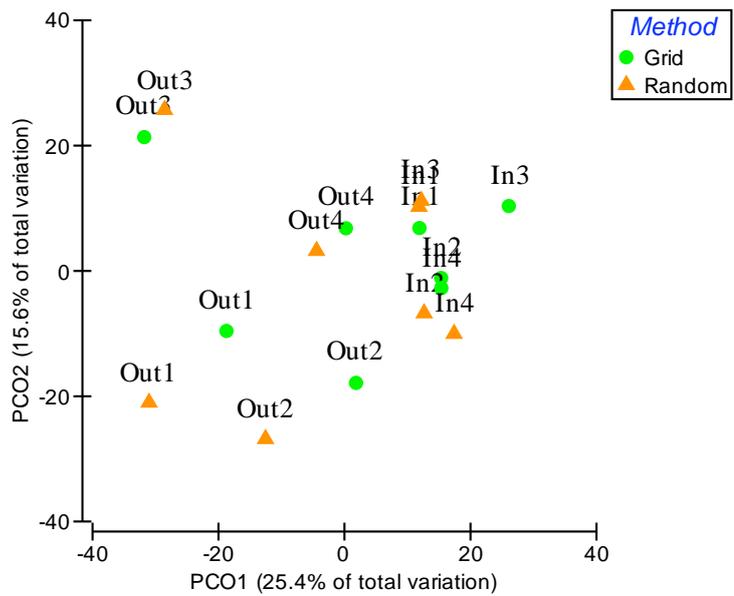


Figure 16. Multidimensional scaling by principal co-ordinate analysis of the assemblage data for each site for the grid and random methods using fifteen quadrats plotted on the first two principal co-ordinate axes. The grid method is indicated by a green circle and the random method is indicated by a yellow triangle. The permutational analysis of variance for these data is shown in Table 17.

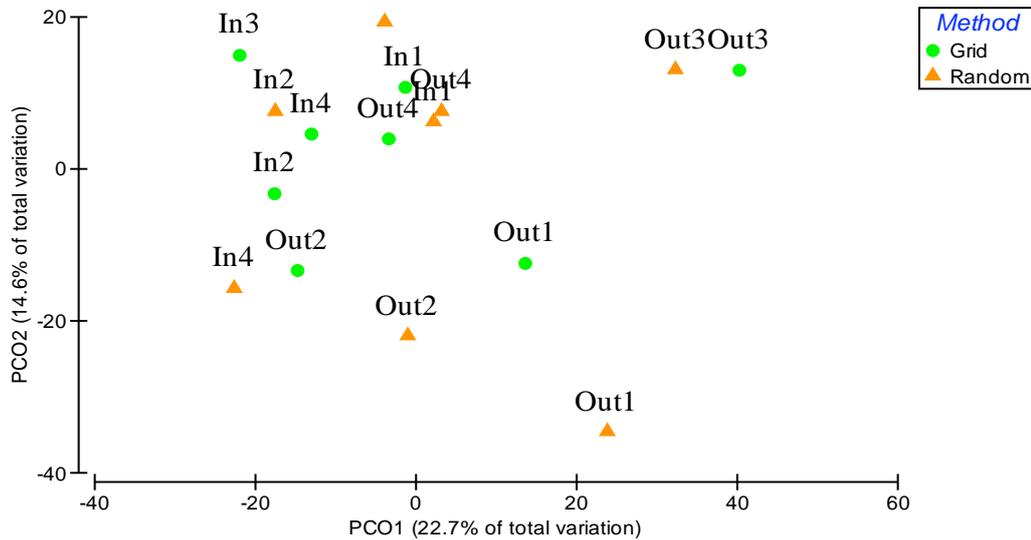


Figure 17. Multidimensional scaling by principal co-ordinate analysis of the assemblage data for each site for the grid and random methods using ten quadrats plotted on the first two principal co-ordinate axes. The grid method is indicated by a green circle and the random method is indicated by a yellow triangle. The permutational analysis of variance for these data is shown in Table 17.

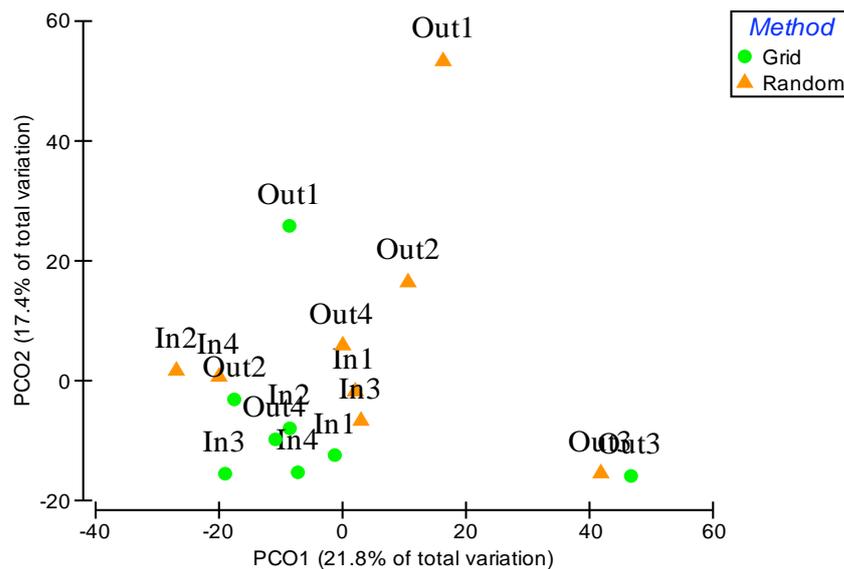


Figure 18. Multidimensional scaling by principal co-ordinate analysis of the assemblage data for each site for the grid and random methods using five quadrats plotted on the first two principal co-ordinate axes. The grid method is indicated by a green circle and the random method is indicated by a yellow triangle. The permutational analysis of variance for these data is shown in Table 17.

The minimum number of quadrats required for effective sampling was also determined by analysing the precision indices for the number of species and individuals. The pattern of the precision indices reinforces the use of at least fifteen quadrats for sampling (Figure 19). However, the precision index for the number of species found by the random method does not appear to be affected by the number of quadrats sampled.

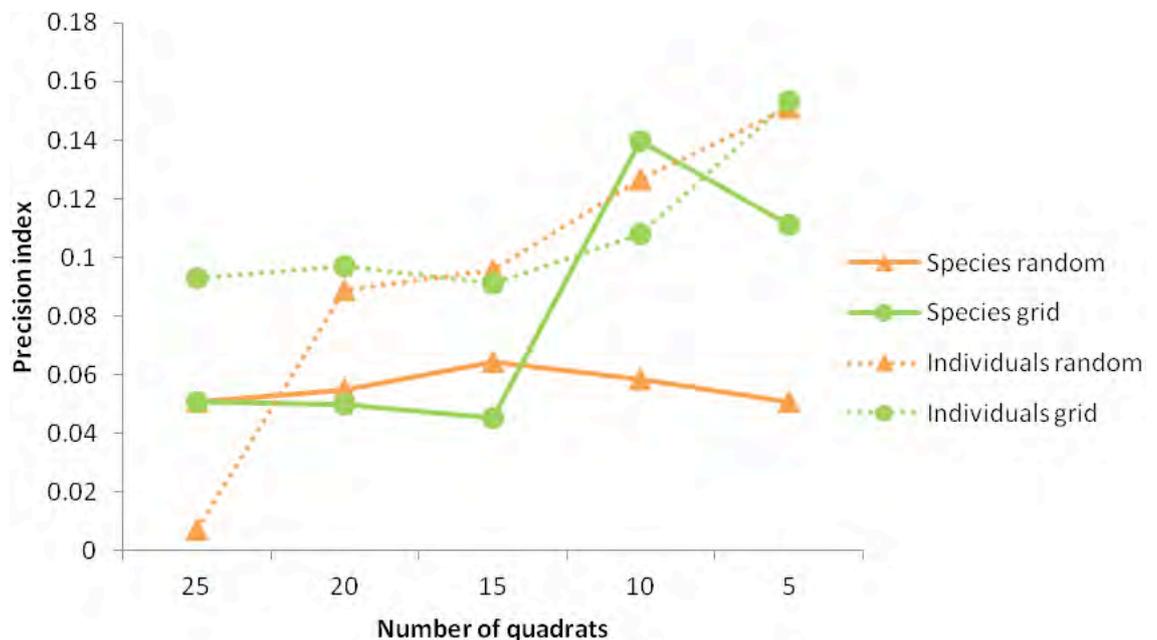


Figure 19. Precision indices for the number of species and individuals using the grid and random methods with reduced numbers of quadrats. An increase in the precision index equates to a more imprecise measurement.

The effect of reducing quadrats in rows, as opposed to the previous method of reducing quadrats in transects, was undertaken by removing rows 1 and 5 from the grid method and removing ten quadrats from the random method (Table 18, Figure 20). There was no change in the significance of Sanctuary or Site(Sanctuary) with the reduction from twenty-five quadrats to fifteen quadrats in this analysis.

Table 18. Probabilities of the assemblage data based on simulations using fewer quadrats. The reduction in quadrats is a result of the removal of rows 1 and 5 from the grid method, and ten random quadrats.

Source	df	p (25)	p (15)
Between sites	[7]		
Sanctuary	1	0.0294	0.0288
Site(Sanctuary)	6	0.0002	0.0002
Within sites	[8]		
Method	1	0.1862	0.1280
Method*Sanctuary	1	0.5490	0.8220
Method*Site(Sanctuary)	6		

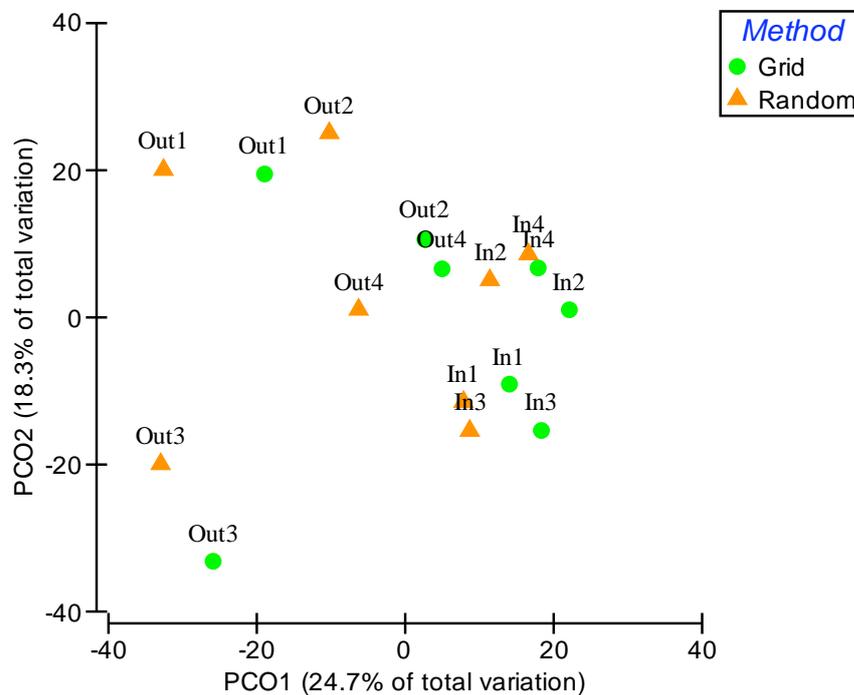


Figure 20. Multidimensional scaling by principal co-ordinate analysis of the assemblage data for each site for the grid and random methods using fifteen quadrats plotted on the first two principal co-ordinate axes. This graph has used a subset of the data set with rows 1 and 5 removed for the grid method and ten quadrats removed for the random method. The grid method is indicated by a green circle and the random method is indicated by a yellow triangle. The permutational analysis of variance for these data are shown in Table 18.

The consistency in the pattern of variation between the two reduced samples and that of the original sample emphasises the ability to reduce the quadrats sampled without loss of information. The patterns found for the two analyses of fifteen quadrats (Figure 16, Figure 20) resemble each other to a high degree of similarity with their pattern of variation. This consistency emphasises that a reduction in quadrats for the grid method can occur through a reduction in the rows or transects, without leading to significantly different results.

An alternative way to reduce sampling effort is to reduce the number of sites sampled, as opposed to the number of quadrats sampled. This analysis is important as the previous study at Ningaloo, as discussed in the introduction, conducted power analyses which determined that more sites needed to be sampled to obtain meaningful results. We found that with fewer than four sites per level of Sanctuary, the difference between sites inside and outside of the sanctuary zone was no longer detected (Table 19, Figures 21-23). With fewer than three sites per level of Sanctuary, no difference between sites was observed.

Table 19. Probabilities of the assemblage data based on simulations using fewer sites. All subsets had equal numbers of sites inside and outside of the sanctuary zone.

Source	df	p (8)	df	p (6)	df	p (4)	df	p (2)
Between sites	[7]		[5]		[3]		[1]	
Sanctuary	1	0.0294	1	0.1080	1	0.3336	1	0.4954
Site(Sanctuary)	6	0.0002	4	0.0046	2	0.0564	-	
Within sites	[8]		[6]		[4]		[2]	
Method	1	0.1862	1	0.4030	1	0.2286	1	0.4988
Method*Sanctuary	1	0.5490	1	0.6032	1	0.3210	1	
Method* Site(Sanctuary)	6		4		2		-	

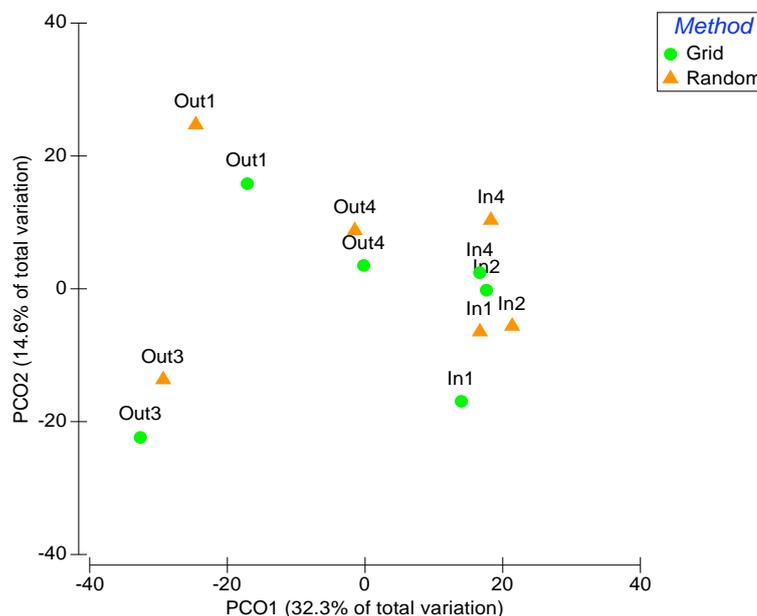


Figure 21. Multidimensional scaling by principal co-ordinate analysis of the assemblage data for each site for the grid and random methods using six sites plotted on the first two principal co-ordinate axes. The grid method is indicated by a green circle and the random method is indicated by a yellow triangle. The permutational analysis of variance for these data is shown in Table 19.

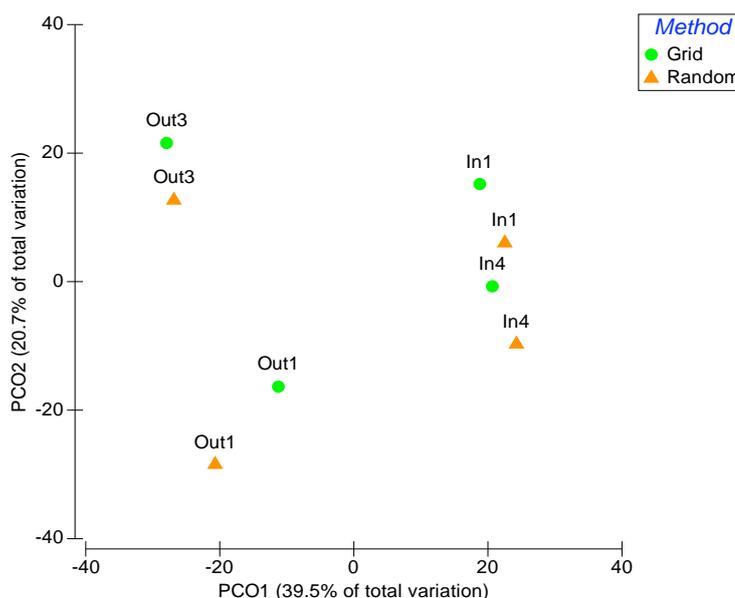


Figure 22. Multidimensional scaling by principal co-ordinate analysis of the assemblage data for each site for the grid and random methods using four sites plotted on the first two principal co-ordinate axes. The grid method is indicated by a green circle and the random method is indicated by a yellow triangle. The permutational analysis of variance for these data is shown in Table 19.

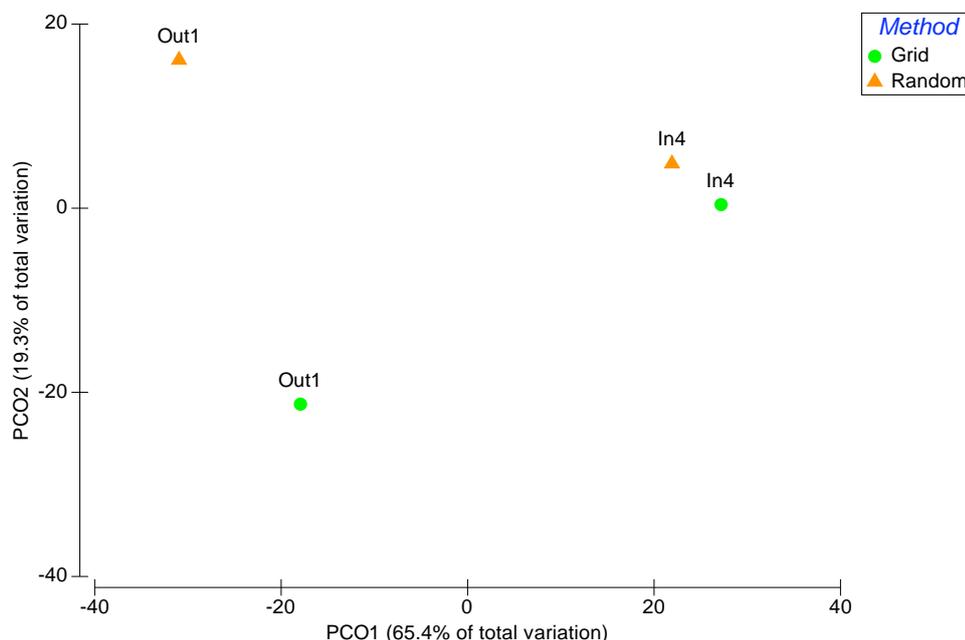


Figure 23. Multidimensional scaling by principal co-ordinate analysis of the assemblage data for each site for the grid and random methods using two sites plotted on the first two principal co-ordinate axes. The grid method is indicated by a green circle and the random method is indicated by a yellow triangle. The permutational analysis of variance for these data is shown in Table 19.

An important aspect of this study was to identify any potential indicator species which could be used as representatives of the whole community. Analysis with the Biota-Environment Stepwise routine allowed us to determine the minimum number of species that needed to be surveyed to yield the same overall pattern found with the original data set. Five species were found that had a correlation of 0.899 to the original data set. These species were *S. mutabilis*, *C. echinatum*, hermit crabs, *S. siphon*, and *E. mathaei*. It should be noted that *Cerithium echinatum* is the one species suggested as an indicator species which was not amongst the ten most abundant species. This result means that measurements of the number of individuals for these five indicator species using the grid and random methods would have resulted in a resemblance to the original data set of 90%. When looking at presence/absence data for the three methods, forty-one species were required to yield a 0.891 correlation to the original data set. This highlights the importance of using abundance measures as opposed to presence/absence when using indicator species.

Temporal variability

Comparison of our data set with that gathered from previous years is important to determine if the sanctuary zone is effective over time. These combined data revealed a significant effect of Date and Site(Sanctuary) (Figure 24, Table 20). Analysis of the contribution of species to the dissimilarity between each combination of years revealed higher levels of some common species in previous years (Table 21).

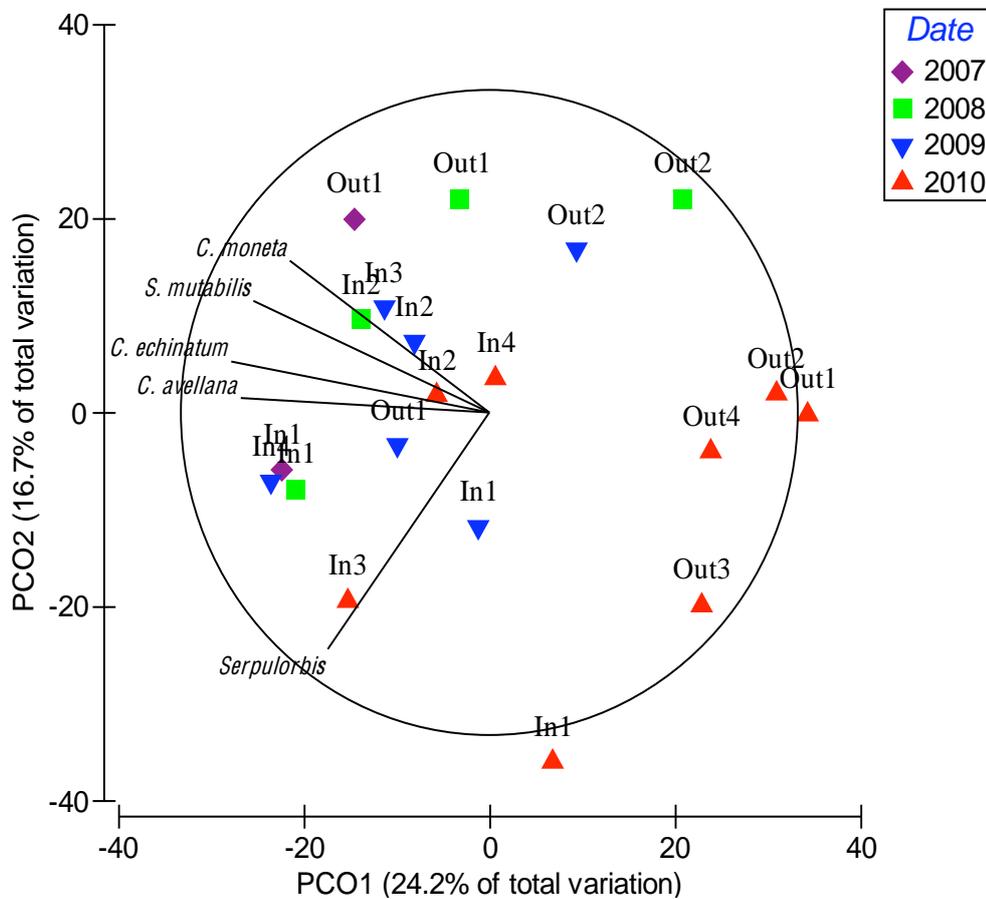


Figure 24. Multidimensional scaling by principal co-ordinate analysis of the assemblage data for each site from 2007-2010 plotted on the first two principal co-ordinate axes. Eight sites were used in 2010 (red ascending triangle), six sites were used in 2009 (blue descending triangle), four sites were used in 2008 (green square), and two sites were used in 2007 (purple diamond). Lines indicate the correlation (> 0.75) of species indicated, with the overlaid circle representing a correlation of one. The species indicated are *Cypraea moneta*, *Strombus mutabilis*, *Cerithium echinatum*, *Cronia avellana*, and *Serpularbia siphos*. The permutational analysis of variance for these data is shown in Table 20.

Table 20. Permutational analysis of variance of the assemblage data from 2007 to 2010.

Source	df	MS	Pseudo -F	p	Unique permutations
Between sites	[7]				
Sanctuary	1	1844.1	1.7413	0.107	4986
Site(Sanctuary)	6	1288.2	1.6432	0.0294	4969
Within sites	[12]				
Date	3	1925.1	2.4556	0.007	4977
Date*Sanctuary	3	839.9	1.0714	0.4072	4983
Date*Site(Sanctuary)	6	784.0			

Table 21. Matrix displaying the dissimilarity values for the assemblage data for 2007 to 2010. Above the diagonal, the species contributing to this dissimilarity are shown with their contribution to the dissimilarity and the year of highest abundance.

	Aug 2007	Nov 2008	July 2009	Feb 2010
Aug 2007	-	Higher in 2007 <i>S. sipho</i> (13.28%) <i>T. haynesi</i> (5.30%) Higher in 2008 <i>S. bilocularis</i> (5.59%) <i>S. mutabilis</i> (5.23%)	Higher in 2007 <i>S. sipho</i> (12.78%) <i>T. haynesi</i> (6.36%) <i>S. bilocularis</i> (6.12%)	Higher in 2007 <i>S. sipho</i> (11.25%) <i>S. mutabilis</i> (7.77%) <i>C. avellana</i> (7.22%)
Nov 2008	45.19	-	Higher in 2008 <i>S. sipho</i> (11.48%) <i>S. mutabilis</i> (7.24%) <i>S. bilocularis</i> (5.86%)	Higher in 2008 <i>S. sipho</i> (9.40%) <i>S. mutabilis</i> (9.21%) <i>S. bilocularis</i> (6.76%)
July 2009	44.22	45.5	-	Higher in 2009 <i>C. sponsalis</i> (8.87%) <i>S. sipho</i> (8.30%) <i>S. mutabilis</i> (6.93%)
Feb 2010	57.78	56.66	53.37	-

The significant Site(Sanctuary) factor can be explained by the usual variation between replicate sites, as seen in all previous analyses. A significant Date factor can be explained by the normal life cycle and variation characteristic of marine intertidal macroinvertebrates. The important finding in this analysis is the lack of a significant Sanctuary factor and Date*Sanctuary interaction. From our previous results, we would have predicted an effect of these two factors. A significant Date*Sanctuary interaction would indicate a change in the relationship, with respect to the composition of the assemblages, between sites inside and outside of the sanctuary zone over the years.

Discussion

By Samantha Cadee

Long term monitoring programs are needed to negate the impacts caused by increased human presence on rock platforms (Godet *et al.* 2009; Steinbeck *et al.* 2005). Volunteer based programs are being developed to try and ease the burden of long term monitoring, but these programs are generally viewed as non-rigorous and therefore inaccurate. This is because these methods tend to be better suited to expert scientists since identification of species is crucial (Bates *et al.* 2007). For these programs to work the methods used need to be both user-friendly and cost-effective, with training given to allow for correct identification. To determine the effectiveness of our three methods we examined how well they were able to determine differences between inside and outside the sanctuary zone and also the minimum sampling effort required to see these differences.

Using univariate and multivariate analyses we examined the effectiveness of our three methods at detecting differences between sanctuary zone status. A significant difference was detected between sites inside and outside of the sanctuary zone when looking at the grid and random data independently, but not when looking at the time search data. If the time search was to be incorporated into a monitoring program it would need to be used in conjunction with one of the other two methods because on its own it is an ineffective sampling tool. This significant sanctuary effect was also only seen when examining the species data. For the grid and random methods to be effective at determining differences between inside and outside of the sanctuary zone, the number of species found must be incorporated into the analyses, you cannot simply count the number of individuals.

More species were found within the sanctuary zone than outside for the systematic grid

quadrat, random quadrat and timed search methods, with grid and random both collecting fairly similar numbers of species inside and outside of the sanctuary zone. Timed search found significantly more species than both the grid and random methods. The grid and random methods were not found to be significantly different to each other in any of the analyses we performed. This may be expected as both methods counted individuals within the same number of quadrats, with the only difference between the methods being the placement of the quadrats on the platform. The timed search was found to be significantly different to the other two methods. This is perhaps due to it only collecting presence/absence data rather than abundances. The species found by time search were also generally rarer, mobile and more conspicuous which may explain why time search picked them up and the quadrats did not. The grid and random methods have very specific placements of quadrats whereas the timed search allows the entire area to be sampled. This allows those rarer and mobile species to be picked up. The conspicuous species are also generally found more often because although the searchers attempted to not bias their samples, if a conspicuous individual was seen during the setting up of the site, the searcher would generally return at some point during the timed search and score it. Also, because numerous people were searching the area at the same time it was difficult to prevent the other searchers seeing when rare species were collected. Every attempt was made to try and reduce these issues but it may still have had some effect on the timed search results. The grid and random teams could only record what was in the quadrats so this bias was not a factor.

When comparing the number of individuals found per site by the grid and random methods an interaction between sanctuary and method was found. The main cause of this interaction appears to be that the grid method only found significantly more individuals than random inside the sanctuary zone, while outside of the sanctuary both methods found roughly the same number of individuals. This difference inside the sanctuary zone may have been due to the unusually high number of individuals found by the grid method at In3. It was found that geographical position of the sites does not affect community composition which means that there was no underlying difference between sites. This unusually high number of individuals therefore may have been due to more thorough searching of the site. We sampled In3 on a morning tide and on that day had the fastest setting up time of all the sites. This meant that we had more time to work before the water became unsuitable. We were also working on the low tide from the beginning of sampling which made searching for invertebrates easier as they are

more visible when the water is low. Sampling methods with minimal setting up are therefore favourable for sampling on rock platforms as conditions are only suitable for a few hours each day. This result highlights the need for effective methods with minimal sampling effort to allow for thorough searching within the time constraints imposed by the low tides.

Tests were performed on the data to determine what level of sampling effort would be required for the grid and random methods to still enable the significant detection of differences between inside and outside of the sanctuary zone. Species accumulation curves were drawn but they did not plateau, so even though we were able to detect a difference between inside and outside of the sanctuary zone, we were not getting a complete picture of the species present at the site. To get a more complete picture of all the species present on the platform more intense sampling would need to be performed. The minimum number of quadrats and sites needed to detect significant differences between sanctuary zone status was then examined. It was shown that a minimum of 15 quadrats would still detect a difference between sites and also between inside and outside of the sanctuary zone for the grid and random methods. It was also found that a minimum of eight sites were required to again detect this difference, however, since only eight sites were used in our study so it may be possible that more sites would produce more meaningful results as it would increase the statistical power of our tests. The statistical analyses used in this study are able to accommodate a greater reduction in the number of quadrats used than the number of sites studied. Using only 15 quadrats may allow more sites to be studied using the same level of sampling effort required for our study. Increasing the number of sites sampled may also allow us to sample across greater spatial variability and increase our chances of sampling areas where negative impacts are occurring.

Another way of reducing the sampling effort may be to only look at indicator species. Losses of information if only indicator species are sampled do not alter to a great extent the results obtained with the full set of data (Puente and Juanes 2008). This may be a useful way of reducing sampling effort since the species accumulation curves do not plateau, so all species present on the platform do not need to be sampled to determine differences between inside and outside of the sanctuary zone. The use of only indicator species will also reduce the logistical difficulties such as time and cost involved in species identification as the searchers will need less training and expertise (Quijon and

Snelgrove 2006). It was found using the abundance data that it was possible to score only five indicator species to produce results that resemble those of the original data. Unfortunately these species are not easily found, they require thorough searching of the area, so the sampling effort required may not actually be any different to if all species were counted. When looking at presence/absence for the three methods, forty-one species would be required. This shows that when looking at indicator species abundance data needs to be collected not just presence/absence. Collecting abundance data on just five indicator species would reduce the number of species required to be known which would in turn decrease the sampling effort. Further studies would need to be conducted on these species to determine if their composition changes over time before they could be used in a monitoring program. These indicator species are also only applicable to Jurabi. The species assemblages differ between the northern, central, and southern parts of the park, so studies in these other sanctuary zones would need to be conducted to determine appropriate indicator species.

The spatial variability of the platforms were also examined to determine if sampling requires the whole platform to be used or if a subset will suffice. The grid and random methods were chosen for our study to enable us to examine this variability. The grid method allows comparison of the separate rows to determine if there is any difference between the inner and outer sections of the platform. Since the random method has the potential to not sample the extremes of the platform, it can also be used in comparison to the grid method to determine if in fact the extremes are required for sufficient sampling. Comparisons of the numbers of individuals and species found in each row of the grid found that there was a significant interaction between site and transect number. No particular site appears to be causing this interaction, but it may in part be due to our sites all being different widths. Some of the sites are half the width of others which may lead to differences in the spatial composition of the invertebrate communities. On average there were more individuals and species found in the outer rows than the inner rows. The first two rows at most sites were much sandier compared with the outer rows which may have an effect on the types of individuals found there. Most of the invertebrates sampled are limited to rocky intertidal platforms which may explain why little was found in the sandy rows. Because of this interaction we are unable to state for certain that the entire platform is required to be sampled in monitoring schemes, however, the random quadrat method did not always sample the extremes of the platform but was still able to detect differences between in and out, so for the purpose of

this investigation it may not be necessary to sample the entire platform. These results show that sampling the extremes of the platform are not necessary in a monitoring program at Jurabi. This may also be another reason why our grid and random results were not significantly different from each other, since they were both sampling the area of platform required to detect differences between inside and outside of the sanctuary zone.

The method required for monitoring of the platforms at Ningaloo Marine Park depends on what is being examined. At Jurabi, the management objectives for the intertidal reef communities are to ensure that the diversity and abundance of these communities are not significantly impacted by trampling and recreational collecting, with the long term target of no loss of community diversity and abundance (MPRA & CALM 2004). To achieve this, quantitative sampling methods are required. Classic quantitative sampling is more precise and generally more appropriate for detecting subtle biological differences and for areas with large numbers of small individuals (Godet *et al.* 2009). Qualitative searches tend to be more biased towards conspicuous individuals as they are easier to see and are therefore picked up more frequently by the searchers (Obermeyer 1998). If measures of both diversity and abundance are required our method of time search could not be used in isolation, as it can only give a measure of species richness. Although timed search does not give an indication of abundance, the method is able to pick up rare species which quadrats may not, making it useful for overall species counts. Timed search could also be modified to estimate abundance particularly if only the five indicator species suggested were used. This may allow time search to detect differences between inside and outside of the sanctuary zone independently from the other methods. Timed search is also fast and easy to perform for experienced searchers so could easily be used in tandem with one of the quadrat methods. A combination of timed search and either the grid or random method using 15 quadrats, would give a good indication of the community diversity and abundance of invertebrates on the platform.

The grid and random methods are not overly different to each other and both would give a good indication of differences between inside and outside of the sanctuary zone. It is essential to be effective when sampling since conditions are only favourable for a short time each day. Initial set up may be a contributing factor when deciding which method to use as the grid does require more initial setting up than the random quadrat method.

Transects have been shown to be better equipped at sampling across platforms that suffer from vertical zonation and spatial variability (Menge *et al.* 1999), so for this reason the grid method may be slightly more favourable to the random. The grid method allows us to look at the spatial variability of the site and also easily compare sections of the platform. Correct identification of species is essential for these methods as it leads to more effective sampling. Because of this, training would need to be implemented so that searchers are competent at identifying macro-invertebrates found on the platform. A combination of the timed search and systematic grid quadrat methods have the potential to be used in a monitoring program at Jurabi. However, additional studies are needed to determine if the community composition changes temporally before they can be adopted.

By Victoria Inman

The aim of this study was to examine the effectiveness of three sampling methods at monitoring macroinvertebrate assemblages inside and outside of the Jurabi Sanctuary Zone. The effect of human influence on habitats has been observed through changes in the composition of the targeted communities in many areas of intertidal platform (Castilla & Bustamente 1989; Castilla & Duran 1985; Dugan & Davis 1993; Hart *et al.* 2005; Keough *et al.* 1993; Moreno *et al.* 1984; Quinn *et al.* 1993). Therefore it was reasonable to predict that if the sanctuary zone was being effective, that our results should find differences in the communities we sampled based on the sanctuary zone status of the area in which they occurred. If we were able to conclude there was an effect of sanctuary zone status, and our methods were unable to determine this effect, this would demonstrate the failure of the methods at the most fundamental level. The grid and random methods consistently showed significant differences between the communities inside and outside of the sanctuary zone. The sites within the sanctuary zone had more individuals and species per site and per quadrat, and different overall assemblages, than the sites outside the sanctuary zone. The timed search detected more species at sites within the sanctuary zone than outside it, but the presence/absence data of the entire community did not reveal a difference between communities inside and outside of the sanctuary zone. The timed search was unable to detect an effect of sanctuary zone status, when there appeared there to be one, and as a result should be excluded as a possible monitoring strategy for the Jurabi Sanctuary Zone.

It was essential to determine the effect of geographical position on the communities, as

sites within sanctuary zones were unable to be placed adjacent to sites outside of the sanctuary zone. Our results found no effect of geographical position on the similarities between the communities we sampled. This indicates that the differences between sites inside and outside of the sanctuary zone were a result of the effect of sanctuary zone status and not simply an outcome of all the sites from one zone being geographically clumped. This is not to suggest that the effect of geographical position is negligible in influencing intertidal assemblages, just that the sites we sampled did not extend over any great geographical distance. Broad scale geographical position does influence community assemblages, and may limit our ability to transfer conclusions from our data to other studies. A previous study into the macroinvertebrate fauna of rocky intertidal platforms at Ningaloo were performed over a larger scale, spanning 2°5'39.24", as opposed to the sites within this study which spanned just 0°0'23.34". This previous study found that both the univariate and multivariate data of the 32 sites they measured were statistically different from one another, with the sites dividing into regional groups. These differences, based on geographical position, were greater than any difference based on sanctuary zone status (R Black, 2010, pers. comm., 3 February). The implication of these results must be taken into consideration before applying local results to broad scale decisions.

Overall, the univariate data showed both the grid and random methods to be extremely similar to each other at determining the number of individuals and species per quadrat and per site. One exception to the similarity between the random and grid methods was the presence of an interaction between these methods and sanctuary zone status for the number of individuals per site. At sites outside of the sanctuary zone there was no difference between the numbers of individuals found between the two methods, but at sites inside the sanctuary zone the grid method found significantly more individuals than the random method. This interaction is most likely a result of the systematic nature of the grid method, with even distribution of quadrats throughout the site. If individuals were aggregated along a gradient, the grid method would sample more individuals than the random method (Miller & Ambrose 2000). Unlike the aforementioned analysis, the analysis of the number of individuals per quadrat only found significant differences between sites. The inconsistency between the two analyses in determining which factors have a significant effect means that the number of individuals is not an appropriate variable to measure for this study.

The timed search found more species than either the grid or random method. This is expected, as this method aims to identify as many species as possible, without providing any information on the abundances of species. Species that are large, but relatively rare, can be easily identified during timed searches, but are unlikely to occur in any of the quadrats because of their patchy distribution (Murray *et al.* 2006). Timed searches identify species which neither the grid nor random method tend to find, as well as providing a more complete species list. Transects and random quadrats were found to consistently underestimate species richness by a significant amount, and required an unrealistic amount of sampling effort before providing an accurate estimate (Miller & Ambrose 2000). The timed search method allows the entire site to be sampled, whereas the grid and random method covered only between 0.78% and 1.67% of the site area.

The multivariate analysis performed in this study revealed more detail on the otherwise general trends found from the univariate analysis. Multivariate analysis is a more sensitive analysis and tends to be more robust to data aggregation (Pagola-Cardé *et al.* 2002). The complete assemblage data showed the random and grid methods to be significantly similar at sampling the intertidal communities. In order to include data from the timed search method, the relative abundances of species was excluded and presence/absence data was analysed. Both data sets (complete assemblage and presence/absence) found a difference between the intertidal communities based on sanctuary zone status. This effect of sanctuary zone status on the assemblages was a result of the random and grid methods. The timed search presence/absence data alone did not detect a difference in the assemblages inside and outside of the sanctuary zone. The significance of the effect of sanctuary zone status is similar between the assemblage data and the presence absence data, $p = 0.0294$ and $p = 0.0272$ respectively. This indicates that if the aim of a study was simply to detect a difference between communities based on sanctuary zone status, collecting presence/absence data would yield similar statistical results compared to collecting the complete assemblage data, which is more time consuming. This demonstrates that a difference between communities based on sanctuary zone status is primarily a result of differing species composition, as opposed to subtle differences in the relative abundances of species. However, it is important that the method employed for sampling allows data to be collected that can address the aims of the monitoring program for which it was intended. The Ningaloo Marine Park Management Plan states that their long term target is to halt the reduction and loss of intertidal community diversity or abundance (MPRA & CALM

2004). Therefore, the collection of presence/absence data would only allow the diversity of the areas to be assessed, and not the abundances of the species. This is opposed to the grid and random methods which are able to address both aims. The presence/absence data revealed a significant difference between the methods, as a result of the inclusion of the timed search data. The species which contributed to these differences are soft coral feathery, *Palythoa densa*, *Holothuria atra*, Holothurian brown, octopus, chiton white, and flatworm brown. These species occurred more frequently in the timed searches than in the grid or random methods. All but the latter two species are easily detectable species. During the timed search these were very obvious to observe, but the likelihood of them occurring in a quadrat was quite low.

Intertidal platforms are known to have high spatial variability and exhibit vertical zonation of species, even over short distances (Murray *et al.* 2006). It was therefore predictable that our results showed that the number of species and individuals varied according to distance from the shore. There were more individuals and species in the seaward rows than the shoreward rows. This result was despite an interaction between the distance from shore and the sites. This vertical zonation of invertebrates on intertidal areas has been well documented (Peterson 1991; Somero 2002; Southward 1958; Stephenson & Stephenson 1972). Our results emphasise the importance of sampling the outer areas of the intertidal platforms, as they contain the highest species richness. One advantage of the grid method is that it allows the spatial variability of the platforms to be analysed, as well as allowing for observations to be made about the changes that occur in different sections of the platform.

The data combined from several years research found no significant effect of sanctuary zone status on the assemblages at Jurabi Sanctuary Zone. The presence of a significant temporal effect implies that temporal changes have more influence on the composition of the assemblages than the sanctuary zone status of the area in which they occur. To determine the effect of sanctuary zone status on intertidal communities the temporal effect must be controlled for by only comparing sites from the same sampling period. However, the data from previous years was based on sampling at 2 sites (2007), 4 sites (2008) and 6 sites (2009). Our results on reduced sampling effort, as discussed in detail below, emphasise the importance of sampling at least 8 sites in order to determine the effect of sanctuary zone status. Therefore, any inability of this data set to determine an effect of sanctuary zone status is most likely a result of low statistical power, as opposed

to a lack of effect. Conclusions concerning changes in the assemblages over time will only be reliable if the sampling uses consistent methodology, the most important factor being a consistent number of replicate sites.

Monitoring programs are constrained by time, money and personnel availability and therefore any means to minimise the amount of time and/or personnel required, whilst not sacrificing data quality or suitability, should be utilised (Durell *et al.* 2005). Our results were analysed to determine any ability to minimise sampling effort through reductions in the number of quadrats and sites sampled. When reducing the number of quadrats sampled by the grid and random methods, differences in the significance of the effect of site are minimal between ten and twenty-five quadrats for the random method and two and five transect lines for the grid method. However, to maintain a significant effect of sanctuary zone status a minimum of fifteen quadrats and three transect lines need to be sampled. This reduction is also supported by the precision indices for the number of individuals and species. Excluding the most seaward and most shoreward quadrats from the grid method allows a reduction in the area being sampled and avoidance of the areas of the platform quickest to submerge, whilst not leading to any significant change in our results. However, our results emphasise that sampling effort should not be reduced through minimisations in the number of sites monitored. Had sampling occurred in less than eight sites there would not have been sufficient statistical power to determine the effect of sanctuary zone status on the intertidal communities. To minimise time and effort constraints, the number of quadrats at each site can be reduced, but the actual number of sites monitored should be at least four for each level of sanctuary zone status.

Sampling surrogate species, species which reflect the broader intertidal community, can reduce sampling time by minimising the number of species measured, but also by eliminating the need for monitoring personnel to have in-depth taxonomic knowledge. This scheme has been utilised successfully in intertidal studies (Smith 2005). Our results show that had sampling included just five species, *Strombus mutabilis*, *Cerithium echinatum*, hermit crabs, *Serpulorbis siphon*, and *Echinometra mathaei*, the data would have resembled the original data by 90%, despite a 96% reduction in the number of species to be identified. The main species contributing to the dissimilarity between sites inside and outside of the sanctuary zone were *S. mutabilis*, *S. siphon*, hermit crabs, *E. mathaei*, and *Septifer bilocularis*. These are also important species to

consider as they are the indicator species for the effect of sanctuary zone status on the communities at Jurabi Sanctuary Zone. The only two species which do not overlap in these two lists of possible indicator species were *C. echinatum* and *S. bilocularis*. Therefore the combination of these two lists would result in a significant reduction in the number of species to be identified, from 128 to 6, whilst maintaining high similarity to the results obtained from the original data set. Unfortunately, the majority of these species are cryptic species, which require significant searching to find. Therefore the time saved by only sampling these species, but ignoring all other species found, may be minimal.

This study is not the first to have compared monitoring methods and sampling effort of intertidal or subtidal areas (Bates *et al.* 2007; Benedetti-Cecchi *et al.* 1996; Dethier *et al.* 1993; Drummond & Connell 2005; Pagola-Carte *et al.* 2002; Pech *et al.* 2004). These studies have primarily measured biomass or cover as representative of abundance, but both biomass and abundance are the recommended variables to measure benthic communities (GESAMP (1980) in Pagola-Carte *et al.* (2002)). Whilst some studies have found little difference in estimates of cover when comparing sampling techniques on rocky intertidal areas, others have determined differences in the effectiveness of methods (Drummond & Connell 2005; Miller & Ambrose 2000). Previous studies found that point contacts along a line transect estimated cover more accurately than a point contact array within random quadrats. It was concluded this was a result of the aggregated nature of the species being sampled. Random quadrats were more likely to either fall completely within or completely outside of an aggregation and were therefore not consistent at estimating cover, whereas the line transects captured the spatial variability. Tremendous amounts of sampling effort were required before transects and quadrats accurately assessed rare species or overall species richness (Miller & Ambrose 2000). This identifies a major weakness of relying on traditional methods of monitoring, such as quadrats and transects.

Our results found the grid and random methods to be so similar as to be effectively interchangeable. The grid method took longer than the random method to complete, however this was most likely a result of individual personnel speed and not an accurate indicator of the method (pers. obs.). The grid method ensures complete coverage of the sample area, and allows easy assessment of the spatial variability of the area during analysis. Whichever of these methods is deemed most appropriate for a monitoring

program, sampling effort should be minimised by reducing the number of quadrats searched, but not the number of sites.

Monitoring programs usually utilise just one sampling scheme to accurately assess an entire community, limiting their potential to accurately estimate the abundance, or even presence, of all species. As a result, multiple sampling schemes should be employed whenever possible. Most important is that the method employed allows data to be collected that can address the aims of the monitoring program for which it is intended. It is essential to determine the most appropriate sampling method for any program, as unjustified use of methods may result in unreliable measurements upon which understandings of communities and on which major decisions about management are based.

By Claudia McHarrie

Within the Ningaloo Marine Park, monitoring is required to determine the effectiveness of sanctuary zones in protecting intertidal species from anthropogenic disturbances. A variety of methods are available for surveying the rock platforms, but each has its advantages and disadvantages when it comes to practicality in the field and statistical analysis of data. This study aimed to determine which method would be most suited for future monitoring of the rock platforms in the Ningaloo Marine Park, the minimum level of sampling effort required, and with the addition of data previously collected, verify whether the sanctuary zone is having an effect on species assemblages.

Systematic grid and random quadrats

The number of species and individuals collected by grid and random quadrats did not differ significantly between methods. However, the grid method found species which were not found by the random method as well as more individuals of *Serpulorbis siphon*, hermit crabs, *Strombus mutabilis*, *Echinometra mathaei*, *Septifer bilocularis* and Coral 2mm brown. *Serpulorbis siphon*, hermit crabs, *Strombus mutabilis*, *Echinometra mathei* and *Septifer bilocularis* were also species which contributed most to the dissimilarity between sites inside and outside of the sanctuary zone. This may suggest that the grid method could be more effective at detecting differences due to sanctuary zone status. Previous studies have reported that a systematic grid method is more likely to yield estimates of the mean that are closer to the true values, compared to randomly placed quadrats (Murray *et al.* 2006; Greig-Smith 1983). This is because the quadrats are

deliberately spread throughout the area ensuring that all dimensions of the sample site have equal sampling effort. This is particularly important when sampling sites with a high degree of spatial variation and is the main advantage of the grid method over the random method (Miller & Ambrose 2000). Randomly placed quadrats may be more likely to fall within or between these patches and consequently overestimate or underestimate the number of species or individuals present on the platform (Miller & Ambrose 2000). Typically invertebrates on intertidal platforms are grouped into three distinct vertical zones, each dominated by different types of species (Raffaelli & Hawkins 1996). Although, numbers of species and individuals varied by distance from shore, with fewer occurring in rows one and two, the rocky platforms at Jurabi had relatively gentle spatial gradients. Furthermore, our sampling was focussed on the midshore, while much of the low and high shore was avoided. Invertebrates on intertidal platforms can also vary spatially due to numerous microhabitats in the form of cracks, rock pools and boulders as well as changes in slope, aspect and rock type (eds Baker & Wolff 1987; Schoch & Dethier 1996). However, rarefaction curves indicated that clumping of individuals of particular species was not extensive enough on the platforms sampled at Ningaloo, to cause large differences between methods. Mapping of grid and random quadrat coordinates after sampling also found the areas covered by samples taken in both methods were similar for a majority of sites. These findings may account for the similar results provided by grid and random methods. Perhaps if a greater area, covering the whole gradient of the platform, had been sampled findings from each method may have differed. Although, even in studies where spatial variation was high, some researchers have found the gain in accuracy from the grid method, compared to the random method, was only slight (Finney 1948, Bourdeau 1953). In some cases estimates obtained from the grid method can actually be less accurate than those based on the random method. This occurs when the pattern of variation in the area is periodic (Bourdeau 1953). Based on analysis of numbers of species and individuals at different distances from shore, there is no clear pattern of spatial periodicity. However, estimates from the grid method could still be erroneous as rocky shores are subject to periodic input of tidal forces (Scherba & Gallucci 1976).

Problems with the grid method can also occur during statistical analysis. When quadrats are placed in a grid design they are not strictly independent because the position of quadrats is determined by the position of the first (Raffaelli & Hawkins 1996). This may lead to problems when carrying out statistical treatments leading to estimates of error as

these are based on the assumption that all sampling units have been chosen independently and at random (Bourdeau 1953). Random sampling by quadrats ensures this assumption is met (Murray *et al.* 2006). Finally, one of the main reasons researchers endorse the use of the grid method is its simplicity and efficiency of use in the field (Huang 2004; Bourdeau 1953). However, we found that the amount of sampling time taken using both grid and random methods was approximately equal, taking an average of 2 to 3 hours at each site. Overall, both methods appear to be similar in the results they provide and both have strengths and weaknesses as a sampling design. As such, it could be worthwhile investigating a combination of the two methods. A mixed random systematic sampling method would remove some of the disadvantages associated with each method, but has not yet been tested in intertidal surveys (Huang 2004). Studies have also demonstrated the effectiveness of a random stratified sampling method for monitoring rocky shores (Murray *et al.* 2006; eds Kingsford & Battershill 1998). This method has been shown to give better accuracy when compared to simple random sampling as it ensures all spatial dimensions are covered at all sites (Miller & Ambrose 2000) and overcomes the potential statistical problems associated with the grid method (Raffaelli & Hawkins 1996). These methods could be worth trialling before undergoing a long-term monitoring program.

Timed search

Numbers of species collected per site, inside and outside of the sanctuary zone were significantly higher using the timed search method, compared with the grid and random methods. This supported findings in studies comparing techniques to assess mollusc and echinoderm diversity on rocky shores, in which more species were found using timed searches, compared to quadrats (Wells *et al.* 2008; Dutton & Benkendorff 2008). Likewise in surveys of freshwater mussels quadrats have been found to underestimate rare species and total number of species unless a very large number of samples are taken (Vaughn, Taylor & Eberhard 1997). Timed search differed from grid and random, primarily due to the occurrence of more *Holothuria atra*, flat worm brown, Holothurian brown, octopus and soft coral feathery. All of these species are either, large, conspicuous or mobile, characteristics of species which are typically found using timed search (Vaughn, Taylor & Eberhard 1997; Hornbach & Deneka 1996). As a consequence of this bias the abundance of certain species may be overestimated leading to misleading results if using this method alone (Hornbach & Deneka 1996). Smaller, less sculptured species can be found using quadrats as this involves a more concentrated

and thorough search of an area (Vaughn, Taylor & Eberhard 1997). The timed searches used in our surveys collected presence and absence data only. When analysing just presence and absence data the timed search was not sensitive enough to detect differences between inside and outside of the sanctuary zone. The species accumulation curves for timed searches at all sites did not reach an asymptote, implying that sites were insufficiently sampled by timed search. This may suggest that by increasing the time spent searching at each site, timed search may find enough species to detect a difference between sanctuary and non-sanctuary zone using presence/absence data. Alternatively, timed search may have been more useful if we had included the collection of quantitative data. Quantitative data is obtained using quadrats and can also be attained using a semi-quantitative form of timed search (Murray *et al.* 2006). In this timed search a smaller area is searched and the number of individuals of each species found is scored in each time interval, rather than just the presence of each species. At the conclusion of the search each species is given an abundance rank (see Hornbach & Deneka 1996; Obermeyer 1998; Metcalfe-Smith *et al.* 2000). This provides an index of abundance for each species at a site, rather than an absolute abundance provided by the grid and random methods. This type of timed search may not be suitable for the sites used in our surveys. Counts may be saturated by individuals of species such as hermit crabs, which were very abundant at each site. This type of timed search would be most useful when targeting particular species which are rare or occur in a particular habitat, meaning that a large area can be covered quite quickly by targeting specific areas (Murray *et al.* 2006). Timed search may still be a valuable means of creating a species list for the area as it is more likely to include larger, less common species. However, for the purpose of determining the effectiveness of sanctuary zones this method would have to be used in conjunction with a quantitative sampling design utilising quadrats. Others have trialled the use of both qualitative and quantitative techniques to survey intertidal platforms and found this to be effective (eds Kingsford & Battershill 1998). If repeating this method a more accurate result could be obtained if the same searchers carried out the method at each site. In our study different people were involved in timed searching at different sites and this could have contributed to differences in the number of species found at each site, rather than the site itself. Others have proposed the use of a standardised check list of common species to minimise between individual differences (Murray *et al.* 2006). Another source of error in the timed search may have come about due to the fact that in sites surveyed in the afternoon (In4 and Out3) sampling was carried out from shore to sea, following the outgoing tide, whereas in the mornings

sampling began from the sea and went to shore as the tide came in. This was done to maximise the amount of searching done at low water level when it is easier to find species, but it may have resulted in a difference in the species being found during different time intervals between afternoon and morning sampled sites. However, from examination of the species area curve and MDS plot for presence/absence data, the two sites sampled in the afternoon remained as different from each other as they did from any other site. Therefore, the starting position for timed searching may not have a noticeable effect on the types of species found and the time interval they are found in.

Sampling effort

Efficiency in sampling studies is essential for maximising the amount of accurate data obtained using minimal time spent sampling (Bates *et al.* 2007). We determined the minimal sampling effort required when using the grid and random methods tested in the field. Sampling should be carried out at a minimum of eight sites, four inside and four outside of the sanctuary zone. Analysis found that, using fewer than eight sites, no difference could be detected between In and Out sites. It has been argued that sampling can be more effective at detecting patterns when many sites are used but fewer replicates are taken within sites. This is because sites will be more likely to encompass a greater spatial scale and more likely to sample an area where a negative impact has occurred (eds Kingsford & Battershill 1998). Alternatively, sampling can be carried out at fewer sites with more samples taken within sites (Murray *et al.* 2006). A number of studies have found high variation in intertidal community assemblages along coastlines requiring the need for sampling a larger number of sites (Underwood & Chapman 1998; Blanchard & Bourget 1999; Archambault & Bourget 1996). However, our findings show no correlation between geographic position and community assemblage, implying that eight sites may be sufficient enough to accurately detect differences between In and Out sites.

Approximately 3 hours are available, around the time of low tide, to carry out the sampling methods at each site once the study area had been established. After this time the water depth becomes too high and sampling becomes more difficult and consequently less thorough and less reliable. If fewer replicates can be taken at each site it may be possible to sample more than one site during a single low tide. This may improve precision and provide more powerful statistical tests (Fairweather 1991). When sampling using quadrats a minimum of fifteen quadrats can be used for grid and random

methods. For the grid method these quadrats can be positioned along transects two, three and four, in the middle of the sample site. When only ten or five quadrats are used, precision decreases and both methods are unable to detect differences in numbers of species and individuals inside and outside of the sanctuary zone. It should be noted that these levels of sampling effort may only apply to the Jurabi intertidal zones and should be tested before applying to other areas.

Indicator species can also be used in monitoring programs to improve the efficiency and cost-effectiveness of sampling strategies as they can reflect the ecological patterns of the whole intertidal community (Smith 2005; Smith *et al.* 2008). Indicator species are particularly reliable and suitable when they are widespread, can be easily sampled and have a stable taxonomy and well known ecology (Smith 2005; Smith 2008). Collection of *Strombus mutabilis*, *Cerithium echinatum*, hermit crabs, *Serpulorbis siphon*, and *Echinometra mathaei* in the grid and random methods would produce the same patterns seen in the overall results. Unfortunately, as a majority of these species are small and can require thorough searching to be found it may involve the same amount of effort to score all species found as we did.

A possible addition to this study could have been to test the effect of a reduction in taxonomic resolution on the ability of a method to distinguish between sites inside and outside of the sanctuary zone. An assessment of the impact of taxonomic level reduction on global intertidal studies found that reduction to genus or family level could be made and differences between sample sites could still be detected (Warwick 1988). Identifying species to genus level results in a 25% decrease in the number of taxa which need to be recognised in the field, while identifying to family results in a 50% decrease. This could be beneficial to monitoring studies as it may allow for input from volunteers, who do not have expertise in identifying intertidal invertebrates and may also substantially reduce sampling time (Bates *et al.* 2007). In the design of our study it would also have been desirable to have sites inside the sanctuary zone more spread out. However, given the limited space inside the sanctuary zone, compared to outside, this was not possible. This resulted in a fairly clumped distribution of the four In sites, with two sites overlapping slightly. Fortunately, given that geographical location of the sites has no relationship with community composition the effect this has on the data collected may be minimal.

Different measures can be used to assess the effect of protected areas and each can produce differing results (Keough & Quinn 1991). In this study measures of species richness (number of species) and abundance (number of individuals) were used. These measures are typically used to summarise the composition of a community in an area and are commonly used in impact studies and marine monitoring programs, particularly in Australia (Keough & Quinn 1991). The use of species richness for detecting impacts has been criticised by some who have found it to be insensitive to detecting impacts that clearly affected populations of individual species. This was because although the overall number of species may not have changed between survey areas or times, the types of species may have changed (Keough & Quinn 1991). We have overcome this problem by running analyses such as MDS plots on the data which reveal the species that were responsible for any differences. The use of species abundance as a measure in impact studies has also come under scrutiny. Although this measure describes the overall community assemblage of an area it may not detect subtle changes between protected and unprotected areas, such as variation in the abundance of a rare species (Povey & Keough 1991). However, this method is valuable as it is non-destructive, with only species that need later identification being removed, and is also easily carried out in the field (Raffaelli & Hawkins 1996). This makes it preferable over some other measures, such as species biomass which requires individuals to be removed and measured or weighed. Species biomass may be favoured over species richness and abundance when a study is trying to assess the effect of a specific impact such as harvesting or collecting on a certain species or group of species (eds Kingsford & Battershill 1998). Density may be used instead of species richness and abundance when a study is attempting to assess the effect of an impact at a population level, rather than community level (Povey & Keough 1991).

Effect of sanctuary zone over time

Systematic grid quadrats, random quadrats and timed searches used in 2010 found significantly more species on the rock platform inside the Jurabi sanctuary zone compared to outside. The grid and random methods also found significant differences in the numbers of individuals among sites. These findings suggest that in 2010 the sanctuary zone is having a positive effect on species assemblages. These effects do not appear to change over time as there was no Date*Sanctuary interaction. Data collected from annual surveys since 2007 showed that species assemblages changed significantly between years, but this change occurred equally inside and outside of the sanctuary

zone. This may mean that although more species and individuals occur inside the sanctuary zone on a spatial scale, suggesting that species are protected from some impacts, there may be additional impacts occurring over time which species inside the sanctuary zone are not protected from. These impacts could be in the form of climate change (Helmuth *et al.* 2006) or trampling (Addessi 1994), which could occur even inside the special purpose zone as human access for shore-based fishing is permitted in these zones (MPRA & CALM 2004). Changes between years could also be explained by variable recruitment (Menge 1991). Alternatively, the effect of sanctuary zone on species assemblages may not have been observed in the three years prior to 2010 because the sanctuary zone was only established in 2005 (MPRA & CALM 2004). Consequently, it may have taken time for the effects of the sanctuary zone to become detectable. Changes in the sampling itself between survey years may also have contributed to the finding of no differences in community assemblages between sites inside and outside of the sanctuary zone. In 2007 only two sites were sampled, in 2008, four sites were sampled, in 2009, six sites were sampled and in 2010, eight sites were sampled. As previously discussed the use of only two, four or six sites results in no detection of a difference in assemblage data between the inside and outside of the sanctuary zone as replication is too low.

Conclusions and recommendations

The object of this study was to compare the practicality and cost-effectiveness of several sampling methods to assist in determining a sampling scheme for the monitoring of sanctuary zones in the Ningaloo Marine Park. Our findings indicate that the grid and random methods are effective at detecting differences between sites inside and outside of the sanctuary zone, both providing the same results. Due to some problems associated with each method, I propose testing a combination of the two methods or a random stratified method. Although timed search finds differences in the numbers of species between In and Out sites, this method finds no difference in terms the types of species found. Therefore, I propose investigating a form of timed search involving collection of abundance data or conducting timed searches for a longer duration. If no alterations are made to the timed search it should only be used in conjunction with a quantitative method if monitoring requires a species list of an area. In regards to the level of sampling effort, a minimum of 15 quadrats along transect lines two, three and four can be used in the Jurabi area and this should be carried out at a minimum of 8 sites, 4 inside and 4 outside of the sanctuary zone. Finally, our data show no effect of

sanctuary zone over time but I propose conducting further surveys over time to verify these results.

By James Taylor

The aim of our project was to determine effective methods of measuring differences between sites inside and outside of the Jurabi sanctuary zone. This was achieved by determining what to measure, how to measure it and the minimum effort required for measurement. This discussion will focus on the comparison of the dependent variables measured, the effectiveness of the methods used, minimal sampling effort, and temporal patterns.

In our effort to determine the appropriate unit of measurement for differences in sanctuary zone status, we considered three measurements: the number of individuals, the number of species, and the assemblage, meaning the consideration of both of these terms concurrently. For a monitoring method to be considered effective, it needed to be able to detect any differences between inside and outside of the sanctuary zone consistently. The number of individuals was analysed by site (single replicate per site) and by quadrat (twenty-five replicates per site) to compare the detection of significant factors. The significant terms identified by these analyses differed and, as we wanted to observe consistent patterns at all levels of scope, we determined that using the number of individuals as a measurement was ineffective when considering the factors involved. The number of species per site and per quadrat did find consistent patterns indicating that the number of species was an appropriate measurement to detect differences between sites inside and outside of the sanctuary zone. For these two univariate measures, we found a pattern of greater numbers of species and more individuals inside of the sanctuary zone. We considered the number of individuals of each species in a multivariate analysis and detected differences in the composition of assemblages between sites inside and outside of the sanctuary zone. Use of the abundances of each species provided the most detail on the composition of the assemblages and has been used successfully in other marine monitoring studies (Guerra-Garcia *et al.* 2006; Hart *et al.* 2005; Pagola-Cardé *et al.* 2002; Steinbeck, Schiel & Foster 2005). The differences detected in the multivariate analysis were due to differing abundance levels of common species found at both locations and not due to any exclusive species. The reduction in data quality of the grid and random methods to presence/absence along with the timed search data also found a difference in composition between the sites inside and outside

the sanctuary zone. This presented a potential reduction of sampling effort without loss of information and so gathering presence/absence data in a method such as timed search was seen as a suitable alternative. Further analysis into the timed search component only of the presence/absence data did not detect any differences between sanctuary zones.

The methods that we tested were yielding consistent patterns across all types of measurements. All three methods were finding more individuals and more species inside the Jurabi sanctuary zone. The timed search method revealed more species than the sampling of quadrats in random and grid methods. The composition of assemblages found by timed search was different than the random and grid methods with those two methods finding similar assemblages. In most instances, grid and random were also finding similar numbers of individuals and species, the exception being grid finding more individuals per site inside the sanctuary zone. As we have previously concluded, the number of individuals was not informative and so this exception does not alter our overall conclusion that the grid and random methods were similar. This similarity was not expected as we had designed the grid method to incorporate spatial variability by covering distances from shore evenly. Our initial supposition was that the grid had failed to detect a vertical zonation pattern characteristic of intertidal rock platforms but our analyses supported the presence of this pattern (Ellis 2003; Stephenson & Stephenson 1972). It revealed more species and individuals in the outer three rows of the platform compared to the most shoreward rows. The similarity may arise from the use of the same number of quadrats in the same spatial area for the two methods. The distribution of the random quadrats is relatively even through the rows and so the random method would also reflect the pattern of higher abundances in the outer three rows. Out of the two methods, grid would be the preferable method as we see no detrimental effect of placing the quadrats systematically and this method allows for easier location of quadrat locations. The grid method samples species across a range of quadrats at each distance from shore which makes the chance of sampling characteristic groupings higher.

The previous methods were seen to be effective but we also encountered some ineffective methods and measures which we will now discuss. Timed search was identifying larger mobile and sessile organisms that were not present in high levels and therefore not encountered in quadrats by chance. The timed search method was seen as

a successful method after the initial analysis of these data. The failure of timed search presence/absence data to detect differences between sites inside and outside of the sanctuary zone highlights the lack of sensitivity due to reduction in the data quality and rules out timed search as a viable method for monitoring sanctuary zones. This method does have some merit in providing an overall snapshot of the species and could be used to generate species lists but it should be limited to these uses and not used to monitor sanctuary zone abundances. The constructed species accumulation curves for the timed search method did not reach an asymptote for any of the sites indicating that more species would have been found at each site with more sampling effort. Species accumulation and rarefaction curves have previously been used successfully in monitoring studies (Colwell, Mao & Chang 2004; Gotelli & Colwell 2001; Scheiner 2003). However, for the sampling effort range that we are looking at, species accumulation curves and rarefied data proved to be uninformative of the differences between sanctuary zone status and method. The rarefied data found that the number of species expected when looking at a set number of individuals was consistent at each site for each method. In addition to being uninformative in the current sampling scheme, analysis of these data by rarefaction is time-consuming and can become quite complex. One of the initial ideas was to use a species accumulation method and so these results justify the rejection of this method as it would have been uninformative of any differences between sites inside and outside of the sanctuary zone. Another method rejected quite early on as a potential monitoring method was that of point contact sampling which required substantial sampling effort and yielded little usable data for this application as the encountering of species was too infrequent. However, this method does provide a good picture of intertidal platform cover and so would be a viable method for any future studies into intertidal platform habitats.

After determining the effectiveness of the measures and the methods, we wanted to observe the effect of reducing sampling effort in different areas to determine an optimal monitoring scheme that had minimal effort but maintained the patterns observed. This was an important aspect in recommending a thorough monitoring scheme that is cost-effective for the managers of Ningaloo Marine Park. Sampling effort reduction was considered in terms of reducing the number of quadrats used, reducing the number of sites used and determining any potential indicator species. The number of quadrats used for the sampling schemes could be reduced to fifteen quadrats while still detecting a difference between sites inside and outside of the sanctuary zone. This reduction of

quadrats could be by removing two entire rows or transects in the grid method. While the reduction of replicates at each site gradually changed the statistical findings, a reduction in the number of sites produced a clear and dramatic loss of statistical power. This was the case with any reduction in sites below the eight surveyed. This finding highlights the power of replicate sites over replicate quadrats in this nested sampling design. Any expansion to increase statistical power of these tests should be done by increasing the replicate sites inside and outside of the sanctuary zones and not by increasing the amount of replicate quadrats used. An interesting finding was that use of abundance levels of five species would have a 90% similarity to the multivariate analysis of the current data set. While this sounds appealing, it has both benefits and drawbacks. Ideally, the five species should be easily identifiable and conspicuous but this was not the case. Of the species indicated, four require considerable effort to find and the fifth, *Echinometra mathaei*, tends to aggregate. On the plus side, an identification key for only five species would be beneficial to untrained volunteers. The same analysis for the minimal species on the presence/absence data found that forty-one species were required for roughly the same similarity. This highlights the need for a systematic method of counting each individual at each site, such as the grid method, for any monitoring technique using these five indicator species to be adopted. It should also be noted that these five species were identified at a point in time and space that may not provide consistent results in future replications as marine invertebrate composition tends to fluctuate seasonally with recruitment and larvae dispersal. The effect of this seasonal variation would have to be studied over time to validate the use of these indicator species as a monitoring method.

We were also interested in observing whether the relationship between the composition of assemblages inside and outside of the Jurabi sanctuary zone changed over time. The comparison with sampling from previous years detected no difference between sites inside and outside of the sanctuary zone and no Date*Sanctuary interaction. This can be interpreted as the Jurabi sanctuary zone being ineffective as any changes in abundance are occurring both inside and outside of the sanctuary zone. However, the previous years had used fewer replicate sites than in 2010 and this may have affected the results as the reduction in the number of replicates sites has been observed to have a drastic effect on the statistical power. A replication of the 2010 data set at a future date might shed some light on whether or not this current result is valid and this would be recommended. If there is still no effect of sanctuary and no interaction term after a

balanced replication of the results then the conclusion of no effect of the sanctuary zone would be justified. This could mean that the usage of sites at Jurabi is not having any impact on the marine intertidal fauna or that the usage of the sites inside and outside of the sanctuary zone is the same, such as platform-based fishing.

It is important to ensure that any recorded variation between sites is due to the effect of the sanctuary zone and not due to variation encountered due to the distance between sites. Spatial heterogeneity in species composition is a common feature in monitoring programmes even over relatively short distances and it is therefore important for the sampling to take this into account (Miller & Ambrose 2000). Testing of the effect of distance between sites on their similarity should be an important and essential test in this and any future studies. For a good experimental design, sites should be placed independent of one another but within close proximity to limit confounding factors such as variation due to distance between the sites. This is done to leave sanctuary zone status as the only factor differing between the two sites. The establishment of the sanctuary zones unfortunately did not have this in mind and there is a stretch of coastline between the In and Out sites at Jurabi that is unsuitable for establishing sampling sites due to the narrowness and patchiness of the rock platform in this area. Our finding of no significant correlation is valuable as it means that any differences that were found between sites inside and outside of the sanctuary zone are not due to spatial variation and validates our findings. It is important to recognise that while spatial variability played no role in the interpretation of these results, data gathered from other sanctuary zones may have spatial variability effects. Our results only consider one sanctuary zone (Jurabi) and so we can only make conclusions on this sanctuary zone and not sanctuary zones in general. Studies in previous years had found that variability within sites inside and outside of several sanctuary zones was higher than variability between sites inside and outside of these sanctuary zones (R Black, 2010, pers. comm., 3 February). The conclusion was that more sites were needed to detect differences. More sites were adopted in our study and we were able to detect differences in sites at Jurabi based on sanctuary zone status. It would be of interest to note whether differences between all sanctuary zones would be detectable with increased sites or if they would still suffer from the effect of spatial variability along the coastline. This is of interest because it would determine whether an overall monitoring programme would be applicable or whether sanctuary zones would need to be considered as self-contained monitoring schemes. While our data set has allowed us to narrow down potential

monitoring methods, their usefulness and efficiency needs to be studied further at other sanctuary zones. This will allow us to ensure that we continue to find statistically significant results without any confounding factors that may occur if one method is adopted universally without any further testing.

This study has identified two main methods that yield potential as a monitoring programme for Ningaloo sanctuary zones. Both of these methods require a minimum of four replicate sites inside of the sanctuary zone and four replicate sites outside of the sanctuary zone, if topography allows for it. The first is the systematic grid sampling method which counts the numbers of each species found in three transects of five quadrats placed parallel to the high shore baseline. This would be beneficial over the similar random method as a marked rope can be placed and moved after each row which allows for a less complicated sample location technique than the use of randomly placed quadrats. The choice of the three transects running parallel to the shore as opposed to perpendicular is an optimisation of the narrow time window at tides because the observation of quadrats in deeper water is quite difficult. The second method looks at the numbers of individuals of the five indicator species identified (*Strombus mutabilis*, *Echinometra mathaei*, *Serpulorbis siphon*, *Cerithium echinatum*, and hermit crabs) in a systematic grid sampling method composed of five transects of five quadrats each. The reason for the use of the original number of quadrats and not the fifteen minimal quadrats is that we cannot anticipate if we would find the same results when reducing sampling effort in two areas. This method therefore requires the use of all twenty-five quadrats and subsequent analysis of these data can determine whether a reduction in the number of quadrats would maintain the statistical significance.

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Appendix

Latitude and longitudes of study sites

Site	Corner of site	Latitude S 21°+	Longitude E 114°+
Jurabi In1	sea left	50' 58.9806"	1' 30.8994"
	shore left	51' 1.2594"	1' 32.037"
	shore right	50' 59.9388"	1' 33.5382"
	sea right	50' 58.1994"	1' 32.0406"
Jurabi In2	sea left	51' 2.34"	1' 25.0788"
	shore left	51' 3.6606"	1' 26.94"
	shore right	51' 2.6388"	1' 28.3188"
	sea right	51' 1.1982"	1' 26.58"
Jurabi In3	sea left	51' 7.2612"	1' 21.72"
	shore left	51' 7.9194"	1' 22.5012"
	shore right	51' 6.6594"	1' 23.5812"
	sea right	51' 5.8782"	1' 22.8606"
Jurabi In4	sea left	51' 3.8412"	1' 24.4806"
	shore left	51' 5.2194"	1' 25.6794"
	shore right	51' 4.197"	1' 27.1194"
	sea right	51' 2.7576"	1' 25.8594"
Jurabi Out1	sea left	50' 51.6582"	1' 50.4006"
	shore left	50' 53.2788"	1' 51.6"
	shore right	50' 52.7382"	1' 53.22"
	sea right	50' 51"	1' 52.1394"
Jurabi Out2	sea left	50' 44.4006"	2' 10.4382"
	shore left	50' 46.4388"	2' 10.4994"
	shore right	50' 46.6794"	2' 12.2382"
	sea right	50' 44.5812"	2' 12.2994"
Jurabi Out3	sea left	50' 48.3606"	2' 0.78"
	shore left	50' 49.2"	2' 1.2582"
	shore right	50' 48.3606"	2' 2.7594"
	sea right	50' 47.5188"	2' 2.3388"
Jurabi Out4	sea left	50' 50.8812"	1' 54.12"
	shore left	50' 52.0794"	1' 54.66"
	shore right	50' 51.54"	1' 56.2188"
	sea right	50' 50.2188"	1' 55.74"

1. Executive Summary
2. Key Findings and Recommendations
4. Communication and Outputs

30 May 2011

4. Communication and Outputs

4.1 Communications and Achievements

4.1.1 Students Supported

1. Bevilaqua, Adelaide May. October 2009. **The microhabitat associations of cowries**

(Cypraea spp.) within the Ningaloo Marine Park This thesis has been submitted to fulfill the requirements for the FNAS Research Project (SCIE4501-4504), University of Western Australia

Supervisors: Dr Jane Prince and Dr Robert Black

(parts included in Research Chapter 3: This Research Project made up one-half of the student's academic study in 2009, and involved participation in field trips in February and July 2009. Adelaide Bevilaqua was responsible for designing and carrying out the sampling and experiments about use of microhabitats by cowries.)

Abstract

Cypraeids occur on intertidal rocky platforms of the Ningaloo Marine Park, but their abundance may be underestimated by standard sampling methods. This research paper endeavored to categorize the cowries present within the Ningaloo Marine Park, their microhabitat associations and the environmental factors controlling abundance and distribution across platforms. Sampling methods explored this microhabitat association on a small and intermediate spatial scale, within and between platforms. Transects parallel and perpendicular to the shore comprehensively measured microhabitat availability with the occurrence and abundance of cowries along with other environmental features. Experimental transplants of the cowries, between apparent "desired" and "undesired" habitat types, tested their response to environmental variables, further identifying the microhabitat preference of cowries. By comparing the data collected between each of the study sites, the differences in species composition and abundance may be explained. Within the northern section of the Ningaloo Marine Park two species of cowry were most abundant within the six sampling sites, *C. caputserpentis* and *C. moneta*. The cowries showed non-random distribution across the intertidal platforms with respect to protected habitat consisting of physical (bare reef substrate) or biological (macroscopic algae) components. Differentiation for microhabitat occurred between the two abundant cowry species, mainly associated with pitted rocky reefs and macroscopic algae. These findings were reinforced as cowries actively selected for these same microhabitats after a 24hr transplantation experiment. These results provide insight into environmental factors that link cowries to their habitat. While this understanding of factors that link cowries to their microhabitat is important for habitat protection, this research has shown that these species are hard to effectively monitor.

Key Words: intertidal rock platform, cowries, microhabitat preference, environmental factors and behavioural response

1. Executive Summary
2. Key Findings and Recommendations
4. Communication and Outputs

30 May 2011

2. Loughridge, Jacob. October 2009. **Do environmental variables explain differences in macroinvertebrate assemblages between intertidal rocky platforms: A Case Study Conducted in the Northern Section of the Ningaloo Marine Park.** *This statement has been submitted to fulfill the requirements of for Conservation Biology and Management research project SCIE 4501-4504. Thesis, University of Western Australia*

Supervisors: Jane Prince and Robert Black

(parts included Research Chapter 7. This Research Project made up one-half of the student's academic study in 2009, and involved participation in field trips in February and July 2009. Jacob Loughridge was responsible for designing and carrying out the preliminary sampling measuring physical features of the platforms in the northern part of the Park.)

Abstract:

The Ningaloo Marine Park has a high diversity of habitat and biology on the intertidal rocky platforms. Repeated biological surveys in February and July (2009) at sixteen sites in the northern section of the marine park, have revealed a large number of species. However, large unexplained variability exists within and between sites on both spatial and temporal scales. To complement the biological data, the sixteen sites in the northern section across a ~90km distance were surveyed to detect whether environmental factors are the cause of this variation. This study identified four environmental variables from each scale of measurement that are significant ($P=0.002$) in explaining assemblage variation between platforms. When platforms were grouped by the magnitude of each environmental variable it revealed a significant difference ($P=0.005$) between the biological assemblages in each group. Continued biological and environmental surveying will improve understanding of seasonal and temporal variations.

3. Cadee, Samantha A., Inman, Victoria L., McHarrie, Claudia G. & Taylor, James P.A. May 2010. **Comparative methods for the monitoring of sanctuary zones on rocky intertidal platforms at Ningaloo Marine Park.** *This thesis has been submitted in partial requirements for Honours in Zoology, School of Animal Biology, University of Western Australia, Crawley, WA, Australia*
- Supervisors: Jane Prince and Robert Black
- (included as Research Chapter 9. These four students worked together full time for 10 weeks on this project which made up 19% of their work for Honours in

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Zoology in 2010. Their project was closely supervised to achieve a focused goal of the WAMSI3.2.2b project, but they made decisions about the details.)

Abstract

For monitoring programs to be successful they require sampling methods that provide accurate data, are cost-effective and repeatable over time. This study tested the application of three sampling methods (systematic grid quadrats, random quadrats and timed search) for use in monitoring macroinvertebrates on intertidal rock platforms in the Jurabi Sanctuary Zone of the Ningaloo Marine Park. Monitoring is required to assess the effectiveness of the sanctuary zones in protecting the invertebrates inhabiting the Ningaloo Marine Park. Eight sites spanning 1.59 kilometres along the intertidal platform were chosen for the study. Four sites lay inside the sanctuary zone (In) and four outside (Out) to allow comparison of the two areas. There was no significant effect of geographical position on the assemblage data. We detected a greater number of species and individuals inside the sanctuary zone than outside with the timed search finding significantly more species than both other methods. The assemblages differed inside and outside the sanctuary zone. This effect was only detected when using the grid and random methods. The assemblage data collected by the grid and random methods did not differ, possibly due to similarities in the number of replicates used and the area covered. The minimum sampling effort required to detect a difference between sites inside and outside of the sanctuary zone was 15 quadrats for both grid and random methods at a minimum of 8 sites. Data collected from 2007 to 2010 found no difference between sites inside and outside of the sanctuary zone. However, this result may be unreliable due to insufficient sampling in previous years.

Keywords: Ningaloo, monitoring, timed search, random quadrats, systematic grid quadrats, rocky intertidal, sampling effort

4. Bond, Todd. June 2010. **Linkages between intertidal invertebrate assemblages and shore platform morphology in the Ningaloo Marine Park, Western**

Australia. *This thesis has been submitted in partial requirements for Honours in Marine Science Honours 2009 - 2010, School of Animal Biology, University of Western Australia, Crawley*

Supervisors: Dr. Robert Black and Dr. Jane Prince, School of Animal Biology, and Dr. Ryan Lowe, School of Earth and Environment (included as Research Chapter 8 with abstract included there and in Executive Summary. This research formed 62.5% of the requirements of Honours in Marine Science during July 2009 to June 2010. Todd Bond brought his knowledge and perspective about coastal geomorphology to describe the exact nature of the rocky intertidal platforms, adding expertise that none of the

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principal investigators had. This work was designed and carried out by Todd Bond, independently of, but closely integrated with, the sampling of the assemblages of macroinvertebrates in July and September 2009. Todd Bond also conducted a Special Topic component of his honours, worth 19% of his honours course, to construct a relational database (using Microsoft Access) to organize all the environmental variables measured by his projects, and the the 2009 sampling of assemblages at 33 sites.)

Abstract

The analysis of spatial patterns is important for scientists specialising in both geomorphology and ecology for understanding variance at different scales. Identifying common processes controlling the morphology of rock platforms and intertidal invertebrate assemblages provides an understanding of the bigger picture and an insight into landscape ecology. The aim of this project was to develop a typology of shore platforms within the Ningaloo Marine Park, Western Australia from the investigation of morphological features measured onsite during visits and offsite using charts and maps to determine if shore platform morphology can help explain and predict an intertidal invertebrate assemblage. Cluster analyses were used to investigate patterns of morphological similarity in all morphological data and subsets of data to determine the best description of site morphology. The subset of data used to determine morphotypes included 10 variables measured both onsite and offsite and identified 5 morphotypes. Site morphology differed regionally with the major differences likely due to wave energy and protection by offshore reef. The patterns of dissimilarity of the assemblages of macro-invertebrates at each site from counts in 20 1m² quadrats were correlated to the patterns of dissimilarity of morphological characters of the site. Furthermore, ordinations of the invertebrate assemblage at each site constrained by the factor morphotype show more defined groupings of sites with the same morphotype. Invertebrate assemblages differed regionally and may be explained by broader scale processes not considered in this project. Predicting the abundance of key animals (i.e. *Cypraea* spp., *Tridacna* spp., *Conus* spp. and Corals) is difficult using this typology but the abundance of other species (*Siphonaria* spp., *Thais orbita*, *Cronia avellana*, *Strombus mutabilis*, and *Septifer bilocularis*) can be predicted with confidence. This project will add base knowledge to rocky coast geomorphology in Western Australia and provide coastal managers at Ningaloo with a tool to guide and focus site-specific invertebrate research.

4.1.2 PhD Theses and Dissertations and Student Placement

No PhD theses or dissertations

Student placement:

Adelaide Bevilaqua -

Todd Bond - Coastal Zone Management Pty Ltd [<http://www.coastalmanagement.com/main/>]

Samantha Cadee - Research Assistant, Helix Molecular Solutions, genetics consulting company [<http://www.helixsolutions.com.au/>]

Victoria Inman - Clerk in Administration, University of Western Australia

Jake Loughridge Contract work with Department of Environment in New Zealand

Claudia McHarrie - Graduate Environmental Scientist for Ecoscape environmental consulting group [<http://www.ecoscape.com.au/>]

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James Taylor - Research Assistant at Royal Perth Hospital School of Pathology and
Laboratory Medicine, University of Western Australia

4.1.3 Publications (other than Theses and Dissertations)

None

4.1.4 Planned Publications

1. Submitted to Marine and Freshwater Research April 2011: *Evidence of large, local variations in recruitment and mortality in the small giant clam, Tridacna maxima (Röding, 1798), at Ningaloo Marine Park, Western Australia* (as Research Chapter 4)
2. In preparations: Spatial and Temporal variation in assemblages of macroinvertebrates on intertidal platforms in Ningaloo Marine Park (as Research Chapter 6)

4.1.5 Presentations (speakers underlined)

Ningaloo Research Symposium 24 and 25 July 2007 Anne Brearley

Second Annual Ningaloo Research Symposium 28 and 29 May 2008 Intertidal invertebrates
2007 pilot study Jane Prince

3rd Annual Ningaloo Research Symposium, 26-27 **May 2009**, Novatel Ningaloo Resort,
Exmouth, Western Australia

Day 1, Session 2 12:30 pm *Intertidal Invertebrates* Michael Johnson, Robert Black, Jane
Prince, Anne Brearley

Bond, Todd. June 2010. **Linkages between intertidal invertebrate assemblages and shore
platform morphology in the Ningaloo Marine Park, Western Australia.**

Seminar as part of fulfillment of Marine Science Honours Degree

Cadee, Samantha A., Inman, Victoria L., McHarrie, Claudia G. & Taylor, James P.A. **May
2010. Comparative methods for the monitoring of sanctuary zones on rocky
intertidal platforms at Ningaloo Marine Park.** Seminar as partial fulfillment
of Honours in Zoology

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Bevilaqua, Adelaide May. October 2009. **The microhabitat associations of cowries (*Cypraea* spp.) within the Ningaloo Marine Park.** *Presentation to research symposium get details*

Loughridge, Jacob. October 2009. **Do environmental variables explain differences in macroinvertebrate assemblages between intertidal rocky platforms: A Case Study Conducted in the Northern Section of the Ningaloo Marine Park.** *Presentation to research symposium get details*

Black, Robert March 2010. *Intertidal Invertebrates.* 12:00 - 12:01, 23 March 2010. Ningaloo Synthesis and Integration Workshop, 23 March 2010, CSIRO, Floreat.

Inman, Victoria. March 2010. *Comparison of methods and intensity of sampling assemblages of species on intertidal platforms at Ningaloo Marine Park.* 9:50-10:10, Tuesday, 30 March, 2010. Ningaloo Student Research Day CSIRO, Underwood Avenue, Floreat.

4.2 Project Outputs

WAMSI 3.2.2b Milestone 16, 12 pp.
 WAMSI 3.2.2b Milestone 29, 1p.
 WAMSI 3.2.2b Milestone 34 and 36, 31 pp.
 WAMSI 3.2.2b Milestone 40, 22 pp.
 WAMSI 3.2.2b Milestone 41, 73 pp.

Intertidal invertebrate species

Workshop booklet draft text
 14 January 2010
 Image: required

edits by R. Black 21 April 2010

Intertidal invertebrates

This project seeks to provide an inventory of the invertebrate organisms that live in the rocky intertidal shores of Ningaloo Marine Park, and an estimate of their abundance.

Background

Researchers are working to assess the assemblages of invertebrate species inside and outside sanctuary zones in the Ningaloo Marine Park.

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This will provide information on the variability of species abundance and community composition in different years (temporal) and over the length of the marine park (spatial), and demonstrate the consequences that variability has for detecting spatial differences and temporal changes.

This study provides the first quantitative description of the distribution and abundance of macro-invertebrates on the rocky intertidal platforms where many visitors have easy access.

Sample results

Project sampling identified:

- Approximately 250 kinds of invertebrates on the rocky intertidal platforms, with most being rare.
- Each platform has an assemblage of invertebrates that differs, sometimes drastically, from all other assemblages, but platforms found in the sanctuary zones cover the entire range of assemblages.

The samples provide a standard for future comparisons of changes over time both inside and outside sanctuary zones in Ningaloo Marine Park.

Data application

Surveys of intertidal platforms are labour-intensive and will not reveal all species.

Given the variation in invertebrate distribution and abundance, it will be difficult to detect differences and change within and between management zones.

Short-term temporal variation is, so far, less than spatial variation, but it is unclear whether temporal changes will be easier to detect than spatial differences.

The results of this study can be used to design future studies aimed at detecting changes in assemblages of intertidal invertebrates over time and detecting differences among areas managed differently.

Contact details

Bob Black (UWA) with Anne Brearley, Mike Johnson, and Jane Prince

4.3 Data Management

Lodged with Luke Edwards for loading into iVEC

Site locations available in Google Earth .kmz files

1. Centers of 36 sites where quadrat samples were taken 2007, 2008, 2009, 2010 and reported on in all the Research Chapters, and where physical data for Research Chapter 8 were collected.
[WAMSI3.2.2bSites.kmz]
2. Corners of 8 sites at northern boundary of Jurabi Sanctuary Zone where data for Research Chapter 9
[WAMSI3.2.2bJurabi8Sites.kmz]
3. Shoreward, southern corners of Transect 1 and some others for areas where *Tridacna maxima* were measured as reported in Research Chapter 4.
[WAMSI3.2.2bGiantClams.kmz]

Raw data files in .csv format (plain text files with comma separated values)

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4. Sample (rows) by species (columns) data for each 1-m² quadrat (1744 rows x 291 species with 10 sample specification columns).
[WAMSI3.2.2bQuadratData.csv]
5. Lengths of small giant clams (*Tridacna maxima*) mapped at 20 sites (3119 rows x 11 columns including identifying information for each length)
[WAMSI3.2.2bGiantClams.csv]
6. GPS readings as UTM values for locations of transects used to map positions of *Tridacna maxima* (giant clams) (404 rows x 6 columns, including sample identification information)
[WAMSI3.2.2bTridacnaUTM.csv]
- 7, 8, 9. Physical features of the platforms in three files (32 rows x 13, 11, 10 columns)
[WAMSI3.2.2bPlatformAttributes.csv]
[WAMSI3.2.2bPlatformQuantative.csv]
[WAMSI3.2.2bFetchAndContour.csv]
10. Latitude and longitude of sites
[WAMSI3.2.2bSiteLatLong.csv]

Metadata files in .rtf format (because one has an image) matched to the raw data files

Metadata files	matching Data files (.csv)
11. WAMSI3.2.2bMetadataForQuadratData.rtf	WAMSI3.2.2bQuadratData.csv
12. WAMSI3.2.2bMetadataForGiantClams.rtf	WAMSI3.2.2bGiantClams.csv
13. WAMSI3.2.2bMetadataForTridacnaUTM.rtf	WAMSI3.2.2bTridacnaUTM.csv
14. WAMSI3.2.2bMetadataForPlatformAttributes.rtf	
WAMSI3.2.2bPlatformAttributes.csv	
15. WAMSI3.2.2bMetadataForPlatformQuantative.rtf	
WAMSI3.2.2bPlatformQuantative.csv	
16. WAMSI3.2.2bMetadataForFetchAndContour.rtf	
WAMSI3.2.2bFetchAndContour.csv	
17. WAMSI3.2.2.bMetadataForSiteLatLong.rtf	
WAMSI3.2.2.bMetadataForSiteLatLong.csv	

Images of 32 sites embedded in .rtf file

18. Text and images about the 32 sites sampled in 2007 and 2009
[WAMSI3.2.2bSitePages.rtf]

As requested for lodging data and metadata

Proforma

19. **WAMSI3.2.2bMetadataProforma.xls**

Image for thumbnail icon

20. **WAMSI3.2.2bBrearleySurfers.jpg**

File of this listing of files

21. **WAMSI3.2.2bMetadataFiles.rtf**

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Metadata Proforma.xls

Please answer the following questions about your WAMSI research datasets and any other datasets you would like to store at iVEC. If you have other documentation that describes the data you collected please also attach with this spreadsheet or just attach that if it answers all these questions.	WAMSI Node Project 3.2.2b Intertidal Invertebrates
What	
What is the title of the study? (e.g. what would like to be the title of the metadata record)	Diversity, abundance and distribution of intertidal invertebrate species in the Ningaloo Marine Park.
What would be some key words for searching for this data?	intertidal, invertebrates, cowries, giant clams, assemblages, power analyses, effect sizes, multivariate analyses, sanctuary zones
What constraints would you place on the data (e.g. legal, usage - purposes that shouldn't use the data). The standard license for WAMSI will be Creative Commons Attribution-NonCommercial-ShareAlike 3.0 Australia (CC BY-NC-SA 3.0) - http://creativecommons.org/licenses/by-nc-sa/3.0/au/deed.en	standard license
Who	
Who did the research? Please list names and the contact details.	Dr. Robert Black (robert.black@uwa.edu.au), Prof. Michael S. Johnson (michael.johnson@uwa.edu.au), Dr. Jane Prince (jane.prince@uwa.edu.au) School of Animal Biology, and Dr. Anne Brearley (anne.brearley@uwa.edu.au) School of Plant Biology, University of Western Australia

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Who is point of contact in case of questions? Please list their contact details - is there a generic contact that could be used to ensure longevity?	Dr. Robert Black (robert.black@uwa.edu.au) +61 8 6488 2232
Who else should be acknowledged? Any links to journal articles?	Participating students: Adelaide Bevilaqua, Jake Loughridge, Todd Bond, Samantha Cadee, Victoria Inman, Claudia McHarrie, James Taylor. No links to Journals.
Why	
Why was the research done? This is the abstract - a brief summary of the content of the research is required including the research intentions	A quantitative pilot study of the composition of the benthic community of macro-invertebrates on intertidal rocky platforms was undertaken to (A) provide detailed information on variation in biodiversity along the length of the Ningaloo Marine Park and (B) determine the appropriate design of a monitoring protocol powerful enough to determine predefined levels of change. These general overall aims were in the context of the Ningaloo Marine Park Draft Management Plan of 2004, which set out a vision of maintaining the ecological values in the Park, and protecting it from adverse human impacts.
How	
How was the research done? (e.g. instrumentation, brief description of procedure)?	We used intensive searches during daytime low tides of replicated (usually 20) 1-m ² quadrats to estimate the abundance of assemblages of macroinvertebrates in sites about 15 x 50 m on 36 selected rocky intertidal platforms. We used differential GPS to survey some features of the sites.
How often were measurements taken? Were they aggregated into a specific unit of time (e.g. day, multi-day, week, month, multi-month, year, multi-year)?	Main sampling was done in August 2007 and July and September 2009, with additional sampling in November 2008, February 2009, February and September 2010.
How are the data currently stored, that is what format is the data? (e.g. GIS shapefiles, compressed AVI etc.) Please provide as much information as possible.	Google Earth .kmz files for locations of sites; .csv files for data on the invertebrate assemblages, maps of giant clams, and physical features of the platforms; .jpeg image files embedded in .rtf word processing files.
When	
When was the research carried out? When were the start and end dates?	July 2007 to September 2010

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Where	
Where was the research done? As a minimum please indicate the 'bounding box' in latitude/longitude (decimal degrees) (e.g. North bound latitude -22.00; West bound longitude 113.00; East bound longitude 114.00; South bound latitude -23.00)	We worked on the intertidal shoreline in Ningaloo Marine Park. The northernmost site was Mildura Wreck (21°47'6.30" S 114° 9'54.52" E) and the southernmost site was 3 Mile Out 2 (23°52'45.54" S 113°29'25.42" E) Box is 21°47'6.30" S to 23°52'45.54" S and 113°29'25.42" E to 114° 9'54.52" E
Where are any other related publications/information about the research published - if any? (e.g. url)	No journal articles yet. Two Research Project theses, one Marine Science Honours thesis and one Zoology Honours thesis (UWA). Details available in final report for WAMSI 32.2.b.
Where in the vertical column of the ocean was the research undertaken? (e.g. minimum and maximum depth)	Intertidal, relative to chart datum about 0.5 m.
Supplementary information - Please attach any further information you think would be useful for future researchers	None.
Image - If you have one handy please also attach a picture (JPEG preferable) that best describes your research. This will be used as the thumbnail image next to the metadata records in the MEST	WAMSI3.2.2bBrearleySurfers.jpeg