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**Mapping and characterisation of the inter-reefal benthic assemblages of the  
Torres Strait**

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1 **Abstract**

2 A comprehensive survey of the benthic assemblages of the Torres Strait was  
3 conducted in order to provide critical baseline information for regional marine  
4 planning, assessing the environmental sustainability of fisheries and understanding the  
5 ecosystems of the region. Over 150 sites throughout the region were sampled with a  
6 modified prawn trawl, towed underwater video, pipe dredge and epibenthic sled. This  
7 manuscript provides a broad overview of the activities undertaken and data collected.  
8 Two thousand three hundred and seventy-two different nominal species were sampled  
9 by the trawl and sled; only 728 by both gears. The towed video was not able to  
10 provide the same level of taxonomic resolution of epibenthic taxa but was particularly  
11 useful in areas where the seabed was too rough to be sampled. Data from the trawl,  
12 sled and video were combined to characterise the epibenthic assemblages of the  
13 region. Data from the towed video was also used to provide a characterisation of the  
14 inter-reefal benthic habitats which was then analysed in combination with physical  
15 covariate data to examine relationships between the two. Levels of mud and gravel in  
16 the sediments, trawling effort and seabed current stress were the covariates most  
17 significant correlated with the nature of the seabed habitats.

18  
19 *Keywords:* Seafloor mapping, benthic environment, aquatic communities, underwater  
20 video, Australia, Queensland, Torres Strait

21

22

## 1 **Introduction**

2 Successful planning for marine conservation goals and environmentally sustainable  
3 fisheries requires a foundation of baseline ecological knowledge, such as:  
4 comprehensive maps of water column characteristics, seabed habitats and species  
5 assemblages. These are vital for implementing some of the tools of regional marine  
6 planning such as the identification of representative areas for biodiversity  
7 conservation, sustainability assessments of fisheries, multiple-use zoning plans and  
8 management strategy evaluations. The cost-effective provision of such information is  
9 a challenge in any region.

10

11 This is no less the case in Torres Strait — a varied and dynamic area (~48,000 km<sup>2</sup>) of  
12 continental shelf between Papua New Guinea and Australia. The region has complex  
13 bathymetry with approximately 350 islands (Geoscience Australia, 2005) and  
14 numerous reefs and shoals, including the northern extents of the Great Barrier Reef  
15 (Figure 1). Most of the Strait is relatively shallow (< 20 m), particularly at its  
16 narrowest (150 km) dimension. This, combined with the out of phase tidal regimes on  
17 either side of the Strait, results in very strong currents, particularly between some of  
18 the reefs and islands (Bode & Mason, 1994), which keep sediments mobile  
19 (Margvelashvili & Saint-Cast, 2007).

20

21 Torres Strait also appears to be an important biogeographic boundary, probably as a  
22 result of low sea level stands during the Pleistocene when the Strait was emergent for  
23 significant periods providing a barrier to gene flow between the Pacific and Indian  
24 Oceans (Chenoweth et al., 1998). This resulted in the formation of sibling species on

1 either side of the barrier, some of which may have since re-merged, while others  
2 remain distinct (Randall, 1999).

3

4 Although the region has a small population and is relatively isolated from major  
5 cities, there is pressure to increase economic development to benefit the local  
6 communities. The major sources of potential impact to Torres Strait benthic  
7 communities are fishing, tourism and shipping. Fishing is an important activity in the  
8 Torres Strait — traditional fishing is vital to the Islander communities and  
9 commercial fishing is the most economically important activity in the region  
10 (Anonymous, 2003). The most valuable commercial fisheries include: prawn and  
11 tropical rock lobster. The Torres Strait provides the only shipping passage from the  
12 east coast of Australia to south-east Asia and because of its numerous reefs and shoals  
13 and shallow depth, the risk of a shipping accident is of concern. Development for  
14 tourism is presently low, but growing and potentially could become significant in the  
15 future.

16

17 This study aimed to provide a wide range of baseline biological information to assist  
18 planning and management of the competing uses of the Torres Strait region. This  
19 manuscript outlines the scope and range of data collected and provides a broad  
20 characterisation of the seabed habitats and assemblages of the Torres Strait based on  
21 towed underwater video data and summarized species data.

22

## 23 **Materials and Methods**

### 24 *Sample design*

1 One of the aims in the present study was to create maps of seabed biota and habitats  
2 and to most efficiently utilise the available field time by locating the sample sites in a  
3 way that representatively sampled the multi-variate 'environment space' by  
4 accounting for the relative importance of each of the physical variables in driving the  
5 biological patterns.

6  
7 Pitcher et al. (2004) collated a range of biological and physical datasets which  
8 included information on the physical environment (bathymetry, sediment grain-size  
9 and composition, bottom water attributes and chemistry (Climatology of Australian  
10 Regional Seas - Ridgway & Dunn, 2002) , ocean colour); basic seabed habitats  
11 (substratum, epibenthos, seagrass and algae) and some trawl samples. Twenty five  
12 variables were selected as potentially being useful for stratification (Table 1).

13  
14 The biological data, most of which were sourced from multiple legacy projects, were  
15 reconciled to useable common-denominator formats. All physical data were  
16 interpolated, resampled and mapped to a 0.01 degree resolution (~1.1 km) grid  
17 covering the Torres Strait region (41, 285 grid cells). Spatial autocorrelation analysis  
18 indicated the average distance between sites should not exceed about  $0.1^\circ$  (~11.1 km)  
19 suggesting that not less than about 400 of these grid cells should be sampled. A 10%  
20 margin was added to this lower limit, thus the design provided for 440 sites, although  
21 the resources of the field mapping project would allow only about two thirds of these  
22 to be sampled. We were hopeful that future funding would allow the complete design  
23 to be sampled at a later date; ultimately, the Torres Strait was to be partitioned into  
24 440 relatively homogeneous regions (or *strata*), such that the expected benthic

1 biodiversity would be homogeneous within each stratum but heterogeneous among  
2 strata. A sampling site would then be selected from each stratum.

3

4 Briefly, the following methods were used to generate the sampling design; the details  
5 are given in Pitcher et al. (2004):

- 6 1. Determine the biotic importance of the physical variables using random forests  
7 analysis<sup>1</sup> (Breiman, 2001) of a comprehensive dataset of 30 benthic statistical  
8 assemblages and 90 single species using a similar set of physical covariates as  
9 collected for Torres Strait as explanatory variables (Pitcher et al., 2002).
- 10 2. Reduce the number of variables using principal coordinates analysis to  
11 facilitate computational manageability and to provide an orthogonal  
12 coordinate space for clustering
- 13 3. Stratify the data in two stages; initially the 0.01 degree cells that had similar  
14 physical attributes were grouped together to form 50 primary strata and then  
15 each primary stratum was partitioned, generating a total of 440 sub-strata. By  
16 performing the stratification in two stages it was possible to raise the level of  
17 sampling effort into uncommon and rarer areas in covariate space that may be  
18 more interesting in terms of biota, although this was at some cost to common  
19 areas.
- 20 4. Choose a single sampling site (0.01 degree cell) from each of the 440 sub-  
21 strata by selecting cells that had the maximum number of neighbours of the  
22 same sub-stratum and were the maximum distance from the edge of the sub-  
23 stratum. This strategy maximized the covariate representativeness and spatial  
24 regularity of the selection, within the desired constraint of the stratification,

---

<sup>1</sup> A random forest is a classifier comprised of many Classification and Regression Trees (CARTs). The output of a random forest is the mode of the output of the individual CARTs

1 and minimized the likelihood of clumps and voids and adjacent, edge and  
2 isolated cells. Isolated cells are undesirable because they are less likely to be  
3 representative of their stratum because of errors in the physical covariates.

4

#### 5 *Field sampling*

6 Sampling was conducted during two voyages. Trawl samples were collected from the  
7 research vessel F.R.V. *Gwendoline May* (18 m; trawler) between 8 January and 2  
8 February 2004. Epibenthic sled and sediment samples, underwater video and CTD  
9 data were collected from the R.V. *James Kirby* (19 m; motor vessel) between 23  
10 March and 10 April 2005.

11

#### 12 Trip 1: Trawl sampling

13 Mobile seabed fauna were sampled by a single high-flying Florida Flyer (head rope  
14 length = 8 fathoms, mesh size = 50 mm stretched, 153 kg No. 3 Bison boards), towed  
15 for 1 km at 2.7 knots. After completion of each tow, very large animals were  
16 identified, photographed, weighed and returned to the sea; all other biota were sorted  
17 to broad taxonomic categories, photographed, bagged, weighed and frozen. Trawl  
18 sampling was completed successfully at 148 sites of 192 visited; the seabed at the  
19 other sites was too rough.

20

21 After field sampling, in laboratories, frozen samples were thawed and identified to  
22 species if possible, weighed and recorded. If identification to species was not possible,  
23 morphologically distinct taxa were grouped to Operational Taxonomic Unit (OTU).

24 Reference specimens of all OTUs were retained.

25

1 Trip 2: Video transects and Epibenthic Sled sampling

2 *Description of the sampling devices*

3 1. *Drop camera*

4 The drop camera system consisted of a camera frame, fibre-optic tow cable, cable  
5 winch, crane, data logging computers, video recorders and display monitors. Paired  
6 video cameras and pressure housings for the power supply and for the telemetry  
7 system were mounted in the galvanised steel frame. The field of view was illuminated  
8 with 1500 W of lighting. Twin parallel lasers, spaced 28.5 cm apart, were fitted either  
9 side of the cameras and projected a reference scale into the field of view. All video  
10 was transmitted to the vessel from the frame via an optic fibre link. On the vessel the  
11 video was recorded onto Panasonic DVCPRO tapes.

12

13 2. *Epibenthic sled*

14 Seabed biota were sampled by a 250 kg galvanized steel epibenthic sled. The sled  
15 opening was 1.5 m wide and 0.5 m high. The sides were solid steel plate, with top and  
16 bottom panels of 20 mm square steel mesh. The one meter long skids were 150 mm  
17 broad and rounded in the front to assist in preventing the sled from sinking into the  
18 substratum so that it sampled epibenthos rather than digging up the substrate. A heavy  
19 steel bar at the base of the front was set an angle of 30° to lift seabed fauna into the  
20 sled. The sled was fitted with bag net made of heavy twine with a 10 mm square  
21 opening.

22

23 *Sampling procedures*

24 While we were aiming to sample a total of 440 sites, resources were not available for  
25 this so a subset was chosen based on their proximity to the prawn trawl grounds. The

1 rationale for this decision was that one of the future applications of this dataset was to  
2 conduct a detailed risk assessment for the fishery and so priority was given to sites  
3 within and adjacent to the trawl grounds. One hundred and eighty-four sites were  
4 visited: 173 were videoed, while 167 sites were sampled with the epibenthic sled.  
5 Ideally all devices would be deployed at all sites, however in some cases this was not  
6 possible either because video revealed the seabed to be too rough to sled or on  
7 several occasions the optic fibre cable of the video broke and, whilst the cable was  
8 being repaired, sampling proceeded with the epibenthic sled.

9  
10 The general procedure at each site was as follows. The video camera was deployed  
11 and lowered to within approximately 0.5 m of the seabed. The camera was towed for a  
12 distance of 500 m at approximately 1.5 knots. Position and distance towed was  
13 recorded by differential GPS every 0.1 s. Video of the seabed was displayed in real  
14 time, enabling personnel to raise and lower the camera in order to maintain altitude  
15 above the seabed during the transect, and to record a real-time summary of the seabed  
16 biota and habitats using a predefined set of codes for substrate and epibenthos types.  
17 The software recorded GPS date/time and position along with each seabed code entry.

18  
19 After completing the camera transect, the vessel turned back along the transect and,  
20 provided the seabed was suitable, the epibenthic sled was deployed and towed at  
21 approximately 2 knots for a distance of 200 m. The vessel's position during the sled  
22 tow was also recorded at 0.1 s intervals throughout the sled tow. The total catch of the  
23 epibenthic sled was sorted into major taxonomic groups on deck. These groups were  
24 allocated a bar-coded sample number, photographed, weighed and depending upon  
25 taxon, either frozen or preserved in ethanol or formalin. All specimens were identified

1 to species if possible; if not, they were identified into morphologically distinct  
2 taxonomic units and assigned to an OTU as described above for the trawl samples.

3

#### 4 *Data analysis*

##### 5 *Trawl and sled samples*

6 Swept area for each sampling device was calculated by multiplying the tow length  
7 (measured using GPS) by the mouth opening of each device. In the case of the sled  
8 this was fixed at 1.5 m; for the trawl this was the head rope length of the net (8  
9 fathoms) multiplied by 0.7 which was the estimated degree to which the mouth of the  
10 net was spread when being towed. Catch rates for all biota from both devices were  
11 calculated as the biomass divided by the swept area and expressed as  $\text{kg}\cdot\text{ha}^{-1}$ .

12

##### 13 *Quantification of epibenthos from U/W video*

14 In the laboratory, the video tapes were analysed in more detail for the presence of  
15 sessile or mobile organisms. All organisms were identified as far as possible and  
16 counted. For those that were difficult to count (e.g. algae, seagrass etc.) an estimate of  
17 percent cover over the whole transect was made, but this data was not used in the  
18 analyses described here.

19

##### 20 *Comparison of biodiversity information obtained from different gear types*

21 The three sampling devices used in this study are selective in the range of biota they  
22 sample. The taxonomic resolution achievable using video is very low compared to  
23 extractive techniques like the sled or trawl and it is not suitable for sampling highly  
24 mobile or very small organisms. However, it is relatively cost-effective, rapid to  
25 deploy and non-destructive. The trawl is suited to sampling demersal organisms such

1 as small fish and crustaceans whereas the sled is efficient at capturing sessile  
2 epibenthos. To compare the biodiversity information content obtained from these  
3 three methods, Gower dissimilarity matrices (Gower, 1971) among all sites sampled  
4 with all three devices were computed (based on  $\log_e(x + 1)$  transformed biomass for  
5 sled and trawl data and  $\log_e(x + 1)$  transformed count data from the video).

6 Dissimilarity matrices were computed for all 3 devices pooled (this was considered to  
7 be the benchmark dataset) and for each device separately.

8

9 For pairwise combinations of these Gower matrices, the Pearson correlation  
10 coefficient was computed by matching each element of the matrices station for  
11 station. A high correlation coefficient would suggest a relatively high agreement of  
12 the relative dissimilarities computed on data from different devices, whereas if the  
13 data from different devices yielded different patterns of dissimilarities among stations  
14 the correlation would be low.

15

16 *Assemblage characterisation using data from trawl, sled and video*

17 The benchmark dataset (data from all 3 devices pooled) described above was  
18 considered to be the most comprehensive in terms of benthic biodiversity information  
19 and so was used to characterise benthic species assemblages. Hierarchical cluster  
20 analysis (Ward's minimum variance) was performed on the Gower dissimilarity  
21 matrix generated by pooling the catch (sled and trawl) and count (video) data from all  
22 three devices.

23

24 *Characterisation of seabed habitats from U/W video*

1 Seabed substrata and sessile epibenthos were keyed in real-time (see Table 2 for  
2 categories used) along with DGPS position (recorded automatically) as soon as they  
3 came into the foreground of the camera's view. Whenever the substratum/epibenthos  
4 changed, the operator entered the new substratum/epibenthos and position. In this  
5 manner the substrate and epibenthos were recorded as segments along the transect. In  
6 order to characterise each video transect, we calculated the total distance recorded for  
7 each substratum and epibenthos category for each transect. Because all transects were  
8 not exactly 500 m, they were then converted to percentages. These data were then  
9 mapped to illustrate the distribution of major biological habitats and substratum  
10 classes throughout the study area.

11

12 The real-time data provided input for a broad characterisation of the seabed habitats of  
13 the Torres Strait. The data used for this analysis included site depth and the proportion  
14 of each 500 m video transect covered by the various epibenthic and substrate  
15 characteristics listed in Table 2. All habitat variables were  $\log_e(x + 1)$  transformed  
16 because of the highly right-skewed nature of their distributions. A Gower's  
17 dissimilarity matrix was computed to estimate the dissimilarity between sites, then  
18 multidimensional scaling with ordinal transformation in 10 dimensions was applied to  
19 reduce the dimensionality of the dissimilarity matrix. Habitat types were then  
20 identified by clustering the 10 dimensional MDS co-ordinates from all videoed sites  
21 using the K-means algorithm. The algorithm requires the specification of the number  
22 of clusters and so a range of possibilities were tried (3 to 15 clusters). The final  
23 number of clusters was chosen by examining the change in Cubic Clustering Criterion  
24 (CCC) and pseudo F statistic. Local peaks in the CCC and pseudo F statistic indicate  
25 appropriate numbers of clusters. The cluster membership for each site was then joined

1 to the matching physical covariates and a form of biplot was produced using the R  
2 statistical package (R Core Development Team, 2007) to illustrate the relationships  
3 between the biological data and physical covariates. Dimensions 1 and 2 from a 2-  
4 dimensional MDS of the habitat data regressed against the suite of 25 physical  
5 environmental variables. Vectors originating from (0, 0) were then overlaid on the  
6 MDS – the length and angle of each vector indicating the degree of relationship with  
7 the biological data. Prior to the regression all variables were standardised to have a  
8 mean of zero and standard deviation of one.

9

## 10 **Results**

11 One thousand five hundred and fifty-one OTUs ("species") were sampled by the  
12 epibenthic sled from 167 sites, 1549 in the trawl from 148 sites and 229 were  
13 identified from the video from 173 sites. Of these, only 14 species were identified in  
14 all three gear types and 728 were caught by both sled and trawl. Many of these were  
15 caught more effectively by one gear than by the other; e.g. the bryozoan *Adeonella* sp.  
16 2 was caught at 69 sites in the sled, but only at a single site in the trawl. Eight hundred  
17 and twenty-three of the OTUs were unique to the sled and 824 to the trawl.

18 Comparison at this level with the video data was difficult because only 29 of the 229  
19 OTUs documented from the video were actually identifiable to species level and none  
20 of those were uniquely sampled by the video.

21

22 The relative sampling rates per swept area could only be compared between the trawl  
23 and sled because only catch rate ( $\text{kg}\cdot\text{ha}^{-1}$ ) data were available for these devices  
24 whereas the video data was recorded as counts. Relative sampling rates of the trawl  
25 and sled differed markedly among different biota. The swept area of the sled was

1 ~0.03 ha and that of the research trawl was ~1.02 ha, but when samples from both  
2 were each scaled to a per ha basis, the sled had higher sampling rates for most biota,  
3 the exceptions being crustaceans for which the trawl sampling rate was ~1.7 times  
4 sled, fishes for which the trawl sampling rate was >10-fold greater than the sled and  
5 Chondrichthyes, which were not well sampled by the small prawn trawl but hardly at  
6 all by the sled (Table 3).

7

#### 8 *Prawn trawl catches*

9 The catch rates of the prawn trawl were dominated by Actinopterygii and Porifera,  
10 catches of Echinodermata, Crustacea and Cnidaria were < one third of those of the  
11 Actinopterygii (Table 3). Catch rates of the other groups were very low.

12 Actinopterygii were caught at all sites by the prawn trawl and catch rates were  
13 generally high throughout the strait (Figure 2), similarly the trawl catch rates of  
14 echinoderms were ubiquitous through the study area. Crustaceans were also caught  
15 throughout the region but catch rates were much greater in the eastern side of the  
16 strait, particularly within and to the south of the commercial prawn trawl grounds. In  
17 contrast, poriferan catch rates were higher in the western region, although they were  
18 also patchier than those of crustaceans in the east (Figure 2).

19

20 Catch rates of molluscs, ascidians and cnidarians were all variable throughout the  
21 strait. Other groups, generally those which are not considered to be caught  
22 representatively by gear such as a prawn trawl, namely Reptilia, Bryozoa, algae and  
23 seagrass (Magnoliophyta) were only caught incidentally throughout the region (Figure  
24 2). Chondrichthyes were rarely caught and significant catch rates of algae were only  
25 found at a single site in the central Torres Strait (Figure 2).

1

2 *Benthic sled catches*

3 The sled catch rates were dominated by Porifera, with approximately 19,078 kg.ha<sup>-1</sup>  
4 kg being taken across the Torres Strait during the survey (Table 3). Catch rates of  
5 Echinodermata, Cnidaria, Ascidiacea and Chlorophyta were approximately one third  
6 of those of Porifera while the catch rates of other groups were relatively insignificant  
7 (Table 3).

8

9 Several groups were distributed fairly widely across the study area. In some of these  
10 there did not appear to be any obvious pattern to catch rates e.g. Actinopterygii and  
11 Crustacea. Other groups however, whilst being caught throughout the strait, had  
12 higher catch rates in particular regions. For example, catch rates of the filter-feeding  
13 groups: Ascidiacea, Porifera, Bryozoa, Cnidaria were much higher in the central  
14 region (particularly in the Endeavour Strait) than either in the west or eastern Torres  
15 Strait (Figure 3). Echinodermata were also widespread, but interestingly, catch rates  
16 were relatively low throughout the prawn trawl grounds to the east of the Warrior  
17 Reef complex. The seagrasses and algae were almost exclusively found in the western  
18 side of the Strait.

19

20 *Video count data*

21 Cnidarians (primarily anthozoans and hydrozoans) dominated the benthos counted  
22 from the video and were observed throughout the area (Figure 4). Actinopterygii were  
23 also commonly observed, although less so in the north-west. Echinodermata were  
24 particularly common in the north and south-west and Porifera featured in the  
25 Endeavour channel and northern parts of the strait (Figure 4).

1

2 *Species prevalence and richness*

3 As is typical of benthic sampling, most of the taxa (OTUs) recorded were rare or  
4 uncommon, occurring in only a very small percentage of the sites surveyed. Most of  
5 the trawl OTUs (~90%) were recorded in less than 10% of trawl sites; 613 OTUs  
6 (~40%) were recorded at only one site, 539 OTUs (~35%) were recorded at only 2-5  
7 Sites (Figure 5a). Only ~6% of the OTUs were prevalent at more than 20% of the sites  
8 and, of these, 23 OTUs had a prevalence >50%. Most of the sled OTUs (~92%) were  
9 recorded in less than 10% of sled sites; 649 OTUs (~42%) were recorded at only one  
10 site and 527 OTUs (~34%) were recorded at only 2-5 sites (Figure 6a). Only <3% of  
11 the OTUs were prevalent at more than 20% of the sites and, of these, only 5 species  
12 had a prevalence >50%. Similarly, 83% of the videoed OTUs were observed at < 10%  
13 of the sites, 53 were only recorded at a single site and only 2 were observed at >50%  
14 of sites (Figure 7a).

15

16 There was an average of  $76.5 \pm 22.3$  (s.d.) OTUs per trawl site, ranging from 28 to  
17 157. Ordering of the most diverse trawl sites also produced a sigmoidal curve (Figure  
18 5b). About 94% of the sites had high species richness ( $\geq 50$  OTUs per site), ~6% had  
19 moderate richness and none low richness. There was an average of  $51.6 \pm 28.0$  (s.d.)  
20 OTUs per sled site, ranging from 6 to 124. Ordering of the most diverse sled sites  
21 produced a sigmoidal curve (Figure 6b). About 47% of the sites had high species  
22 richness, ~51% had moderate richness and only <2% had relatively low richness ( $\leq 10$   
23 species). By comparison, the videoed sites identified an average of  $14.6 \pm 11.4$  (s.d.)  
24 OTUs per site, with a range of 1 to 55. Only two sites had a high species richness and  
25 at 20% of sites  $\leq 5$  OTUs were observed (Figure 7b).

1

2 *Comparison of biodiversity information obtained from different gear types*

3 In the comparisons of dissimilarity indices generated from the three gears, the  
4 combined dataset was considered to be the benchmark. Patterns in dissimilarity  
5 among sites were generated from the sled data were 73% similar to the benchmark,  
6 those from the trawl data were 65% similar while those from the video were 29%  
7 similar (Table 4). Similarities between the three separate devices ranged from 15  
8 (sled and trawl) to 20% (sled and video).

9

10 *Assemblage characterisation using data from trawl, sled and video*

11 Results of the gear comparison showed that each sampling device was capturing  
12 different aspects of the biodiversity and so data from all three devices was pooled to  
13 generate a more comprehensive picture of the benthic assemblages. Cutting the  
14 dendrogram generated by the hierarchical clustering of the pooled trawl, sled and  
15 video data at a dissimilarity of 0.6 gave 9 assemblages which could be summarised as  
16 follows:

17 Assemblage 1 (Number of sites,  $n = 1$ ; number of OTUs,  $s = 183$ ): This assemblage  
18 was dominated by algae (Phaeophyta and Chlorophyta), Ascidiacea, Echinoidea and  
19 Demospongiae. It was characterised by a single site in the north-west (Figure 8).

20 Assemblage 2 ( $n = 7$ ;  $s = 621$ ): Consisted of large amounts of Demospongiae,  
21 Crinoidea, Chlorophyta, and Florideophyceae. Although uncommon, this assemblage  
22 was fairly widespread throughout the strait (Figure 8).

23 Assemblage 3 ( $n = 1$ ;  $s = 194$ ): Largely consisted of Ascidiacea, Rhodophyceae,  
24 Crinoidea, Hydrozoa and Demospongiae and was found off the northern tip of Cape  
25 York (Figure 8).

- 1 Assemblage 4 (n = 19; s = 1008): Characterised principally by a very large amount of  
2 Ascidiacea and lesser amounts of Magnoliophyta, Crustacea, Anthozoa,  
3 Florideophyceae and Rhodophyceae. Assemblage 4 was widespread, but mostly found  
4 in the eastern strait (Figure 8).
- 5 Assemblage 5 (n = 20; s = 883): Consisted mainly of Actinopterygii, Phaeophyta,  
6 Florideophyceae, Ascidiacea, Crinoidea, Crustacea and Magnoliophyta. Assemblage 5  
7 was common throughout the central and eastern Torres Strait (Figure 8).
- 8 Assemblage 6 (n = 10; s = 687): Consisted primarily of Bryopsidophyceae,  
9 Ascidiacea, Calcarea, Chlorophyta, Actinopterygii, Demospongiae and Bilvalvia.  
10 Assemblage 6 was mostly located in the western and far northern strait (Figure 8).
- 11 Assemblage 7 (n = 17; s = 1041): Comprised largely of Crinoidea, Ascidiacea,  
12 Anthozoa, Chondrichthyes and Demospongiae. Assemblage 7 was mainly located in  
13 the western and far northern strait (Figure 8).
- 14 Assemblage 8 (n = 6; s = 613): Consisted mainly of Chondrichthyes, Ascidiacea,  
15 Demospongiae, Florideophyceae, Echinoidea and Asteroidea. This assemblage was  
16 mainly located in the eastern strait (Figure 8).
- 17 Assemblage 9 (n = 10; s = 818): Consisted mainly of Actinopterygii,  
18 Florideophyceae, Chondrichthyes, Crustacea, Demospongiae and Asteroidea. This  
19 assemblage was widespread throughout the strait (Figure 8).
- 20 Assemblage 10 (n = 16; s = 935): Consisted mainly of Actinopterygii, Crustacea,  
21 Magnoliophyta, Chlorophyta and Anthozoa. This assemblage was confined to the  
22 eastern strait (Figure 8).
- 23
- 24 *Habitat recorded by towed video*

1 The towed video transects indicated that algae and seagrass dominated the epibenthos  
2 of western Torres Strait, while sites in the northern central area around the Warrior  
3 reef complex were predominately bioturbated sediment (Figure 9). Areas of  
4 gorgonian and whip garden were common in the eastern and south eastern parts of the  
5 Strait, while hard coral was encountered sporadically in high current areas and/or near  
6 reefs. Sponge garden was present in the northern and southern areas (particularly on  
7 the western side of Cape York), but not commonly observed in the central Torres  
8 Strait. While most western and northern video transects contained a high proportion of  
9 some form of biohabitat, the seabed of many of those in the southeast and eastern  
10 parts of the study area were relatively sparsely covered (Figure 9). The video  
11 indicated fairly clear differences in the distribution of major sediment types  
12 throughout the Torres Strait. Much of western Torres Strait was dominated by sand  
13 and coarse sand, while rubble dominated the northwest (Figure 10). The northern  
14 central and part of the northeast was dominated by silt whereas the east and southeast  
15 was mostly sand with some rock. Sand waves were found in the west, southern and  
16 central parts of the Strait (Figure 10).

17

#### 18 *Identification of habitats – clustering of real-time video data*

19 The local peaks in the Cubic Clustering Criterion and the Pseudo F statistic indicate  
20 possible choices for appropriate numbers of clusters; these occurred at 3, 7, 11 or 14  
21 clusters (Table 5). The smaller the number of clusters the more generalised the  
22 information is for each cluster and so choosing the appropriate number of clusters is a  
23 compromise between diagnostic performance and biophysical information content.  
24 Seven clusters representing benthic habitats were used in this study in an attempt to

1 maximise the amount of biophysical information whilst retaining an acceptable level  
2 of diagnostic performance (Table 5). The habitats were characterised as follows:

3

4 Habitat 1 (Number of sites, n = 16): Depth was variable with a relatively high cover  
5 of sponge garden with some gorgonian garden, hard coral and algae. The substrate  
6 was mostly coarse sand or gravel. In general these habitats were found in the western  
7 strait (Figure 11).

8

9 Habitat 2 (n = 24): Mostly shallow sites (~10m) having a moderate to high cover of  
10 sponge garden, seagrass and algae and a low cover of whip garden and gorgonians.  
11 The substrate was almost exclusively coarse sand with some rubble. This habitat was  
12 located in the north-western and south-western parts of the strait (Figure 11).

13

14 Habitat 3 (n = 16): These sites were deeper than those of habitat 2 (10 to 20 m) and  
15 consisted of mainly bare substrate (mud-silt or sand-gravel) with no epibenthos, algae  
16 or seagrass. They were all located in the northern and central parts of the strait (Figure  
17 11).

18

19 Habitat 4 (n = 18): Deep sites (mean depth = 28.3 m) having a high cover of bare  
20 bioturbated silt. These sites were mainly in the north with a couple occurring in the  
21 southeast (Figure 11).

22

23 Habitat 5 (n = 21): Shallow sites with a high cover of algae, sponge garden and  
24 seagrass on a sand substrate, occurring predominantly in the western parts of the strait  
25 (Figure 11).

1

2 Habitat 6 (n = 37): Deep sites, largely devoid of epibenthos except for small patches  
3 of sponge, gorgonian and whip garden. The substrate was predominantly sand and  
4 they were found largely in the south-east and north-east (Figure 11).

5

6 Habitat 7 (n = 36): These sites were generally of intermediate depth, largely bare  
7 substrate with patches of algae, sponge alcyonarian and seagrass. The sediments were  
8 mainly sand, coarse sand and dunes and they were widespread throughout the strait  
9 (Figure 11).

10

11 *Relationships between the videoed habitat and physical patterns*

12 Only 7 of the 25 physical covariates were significantly or almost significantly ( $p < 0.1$ )  
13 correlated with either of the first two dimensions of the MDS of the coarse-level  
14 habitat data. The largest coefficients were in the first MDS dimension for levels of  
15 gravel, mud, depth and trawling effort (Table 6). Habitats 3 and 4 were associated  
16 with higher levels of mud (GA\_MUD) and Habitats 6 and 7 with high levels of  
17 trawling effort (TRWL\_EFF\_I; Figure 12). Habitats 1 and 2 were associated with low  
18 levels of current stress, gravel, shallow depths (M\_BSTRESS, GA\_GRAVEL,  
19 BATHY) and to a lesser extent with annual mean and variability of turbidity levels  
20 (SW\_K40\_YAV, SW\_K490\_YSD). Habitat 5 was not clearly associated with any of  
21 the covariates.

22

## 23 **Discussion**

24 In order to ensure the sampling of the biological assemblages of the Torres Strait was  
25 as comprehensive as possible, this study employed a variety of sampling gears

1 including a trawl, an epibenthic sled and towed underwater video. The catchability of  
2 different groups of biota varied widely across the different gears as indicated by the  
3 comparison of the dissimilarity matrices generated among sites for each device  
4 separately. The sled and video were more suitable for sampling more sessile, slow-  
5 moving biota and trawl for more mobile demersal species. The trawl was designed to  
6 catch penaeids and caught crustaceans more effectively than the sled. It was also  
7 much more efficient at catching teleost fish and elasmobranchs. The towed video was  
8 able to be deployed in areas where the seabed was deemed to be too rough to sled or  
9 trawl, although the taxonomic resolution was much lower than that obtained by the  
10 extractive methods. A few of the more characteristic epibenthic species were able to  
11 be identified from video, but most could only be identified to phylum.

12

13 Together the sled and trawl sampled a highly diverse seabed biota of more than 14  
14 phyla and 2372 species, of which almost a third were sampled by both devices, a third  
15 were unique to the sled, and a third were unique to the trawl. While the sled samples  
16 were rich with over 50 taxa per site on average, the trawl samples averaged about 77  
17 taxa and were less variable. This may have been due to the difference in tow lengths  
18 between the two devices – 200 m for the sled and 1000 m for the trawl. Thus the trawl  
19 more consistently sampled local populations representatively (particularly of fishes  
20 and crustaceans), whereas the sled sampled all other biota better, though with greater  
21 variability.

22

23 The comparison of dissimilarity matrices generated from the different sampling gears  
24 reinforced the fact that the gears were largely sampling different assemblage patterns,

1 suggesting that data from all three should be combined in order to describe the  
2 biodiversity of the area more comprehensively.

3

4 The assemblage data generated from the video was much less similar to the  
5 benchmark dataset (all three gears combined) than either the trawl or sled data alone.  
6 This stems from the considerable difficulty in identifying and quantifying organisms  
7 from video as well as the limited observability resulting from variable visibility and  
8 camera movement in rough sea conditions. Nevertheless, the video data was useful in  
9 that it provided some information on areas where the seabed was too rough to trawl  
10 (17 sites). Although not analysed in this study, video data can give information on the  
11 within-tow spatial distribution of epibenthos. This contrasts with the sled or trawl  
12 which integrate the catch over the whole tow. The video data also provided a “rapid  
13 assessment” method for documenting the benthic habitats in terms of substrate and  
14 broad categories of epibenthos.

15

16 As is typical of biological sampling, a large proportion of these taxa occurred in only  
17 one or a very few sites. This, and patterns of the species accumulation curves, indicate  
18 that many more seabed species in Torres Strait remain to be discovered. Pitcher et al.  
19 (2004) used a large amount of biological and physical data to produce a stratified  
20 sample design for this survey. Based on spatial autocorrelation distances, an average  
21 distance between sites of approximately  $0.01^\circ$  (~1.11 km) was chosen which resulted  
22 in 400 sites throughout the study region. A 10% margin was added to this lower limit,  
23 giving 440 survey sites. Unfortunately, the resources available for this survey were  
24 insufficient to permit sampling all 440 sites; less than half this number were sampled.

1 For any future surveys in the area a high priority would be given to sample strata not  
2 sampled during this survey.

3

4 Although some groups were ubiquitous in their distribution across the strait (e.g.  
5 Actinopterygii), others showed clear distributional patterns. Seagrasses were found  
6 almost exclusively in the west and Crustacea dominated the east. The filter-feeding  
7 groups Ascidiacea, Porifera, Bryozoa, Cnidaria were much higher in the central  
8 region than either in the west or eastern Torres Strait. This distribution matches that of  
9 the highest currents in the area (Saint-Cast & Condie, 2006). Long et al. (1997a)  
10 demonstrated a positive correlation between seabed current stress and the distribution  
11 of sessile epibenthos in the Torres Strait and similar relationships have been identified  
12 in other areas e.g. the Gulf of Carpentaria, Australia (Long et al., 1995) and the  
13 Bristol Channel in the U.K. (Warwick & Uncles, 1980).

14

15 These patterns were also reflected in the distribution of the assemblages and habitats –  
16 some were widespread, but many were confined to either the eastern or western side  
17 of the strait. Similar longitudinal patterns have been found for reef-associated fauna  
18 and flora (e.g. reef fish, holothurians, seagrasses) across the Torres Strait (Haywood et  
19 al., 2007).

20

21 Sediments across the majority of the study area were mostly sand or silt. Silt  
22 dominated around the Warrior Reefs, while coarse sand occurred principally in the  
23 west and southwest. Extensive areas of rubble were found in the northwest while the  
24 remaining areas were sandy in nature. These general patterns matched those of  
25 previous studies in the region (Skewes et al., 1996, Long et al., 1997b). During a

1 study to examine the feasibility of a potential gas pipeline route along the seabed  
2 between PNG and Cape York, Long et al. (1997b) found significant areas of hard  
3 substrate, particularly in the narrow channels between reefs. In contrast, the present  
4 study found very little rock or reef, probably because very few of the sample sites  
5 were located close to reefs.

6

7 This manuscript has provided a broad overview of the activities undertaken and data  
8 collected during an intensive survey of the Torres Strait inter-reefal benthic habitats.  
9 Future work will focus on searching for surrogate relationships between organisms  
10 and the physical covariates and using these to predict species distributions. The  
11 species distributions, in combination with historic data on the fine scale patterns of  
12 prawn trawling effort will be used to produce a risk assessment for a range of trawl  
13 bycatch species.

14

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Accepted manuscript

1 **Table Captions**

2

3 Table 1. List of physical covariates used in the sample design and regression

4 analyses.

5

6 Table 2. Categories of substrate and epibenthos used in classifying the realtime

7 towed underwater video footage.

8

9 Table 3. Overall total and mean sampling rates ( $\text{kg}\cdot\text{ha}^{-1}$ ) for the major Phyla by  
10 sled and trawl indicating relative composition and relative catchability.

11 Ratio is the ratio of the mean trawl sampling rate relative to that of the  
12 sled.

13  
14 Table 4. Pearson correlation coefficients of Gower dissimilarity matrices among  
15 all sites sampled with all 3 gears (trawl, sled and video;  $n=107$  sites).

16  $R^2$  values are shown in parentheses. \* =  $P<0.0001$ .

17

18 Table 5. Cluster diagnostics: Cubic Clustering criterion (CCC) and Pseudo F  
19 statistics for K-means clustering of the coarse level habitat data.

20

21 Table 6. Regression coefficients for the significant and almost significant  
22 covariates for a regression of the first two dimensions of an MDS of  
23 the coarse level habitat data on the physical covariates.

24

25

26

1

2 **Figure Captions**

3

4 Figure 1. Torres Strait – Map showing the study area and the prawn trawl  
5 grounds.

6

7 Figure 2. Distribution and abundance of classes of catch from the prawn trawl.  
8 The area of each bubble is proportional to the total catch rate ( $\text{kg}\cdot\text{ha}^{-1}$ ).  
9 Echinoderm = Echinodermata, Actinopter = Actinopterygii, Chondricht  
10 = Chondrichthyes.

11

12 Figure 3. Torres Strait – Catch rates from the benthic sled collected by the  
13 F.R.V. *James Kirby* during February to March 2005. The area of each  
14 bubble is proportional to the log of the catch rate ( $\text{kg}\cdot\text{ha}^{-1}$ ). Echinoderm  
15 = Echinodermata, Actinopter = Actinopterygii.

16

17 Figure 4. Torres Strait – density of epibenthos observed on the towed underwater  
18 video collected by the F.R.V. *James Kirby* during February to March  
19 2005. The area of each bubble is proportional to the log of the count. $\cdot\text{ha}^{-1}$   
20 <sup>1</sup>. Echinoderm = Echinodermata, Actinopter = Actinopterygii,  
21 Chondricht = Chondrichthyes.

22

23 Figure 5. Patterns of (a) prevalence and (b) richness of 1551 species at 166 Sled  
24 stations.

25

- 1 Figure 6. Patterns of (a) prevalence and (b) richness of 1549 species at 148 Trawl  
2 stations.  
3
- 4 Figure 7. Patterns of (a) prevalence and (b) richness of 229 OTUs at 171 video  
5 stations.  
6
- 7 Figure 8. Torres Strait – voronoi mapping of the benthic assemblages identified  
8 by hierarchical clustering of the combined trawl, sled and video data.  
9
- 10 Figure 9. Torres Strait – Distribution of major classes of epibenthos identified  
11 from towed underwater video taken during the second survey in  
12 March-April 2005.  
13
- 14 Figure 10. Torres Strait – Distribution of major classes of sediment identified from  
15 towed underwater video taken during the second survey in March-April  
16 2005.
- 17 Figure 11. Torres Strait – voronoi mapping of the benthic assemblages identified by  
18 K-means clustering of the real-time video data.  
19
- 20 Figure 12. Biplot of the MDS of the coarse-level habitat data with vectors  
21 representing the statistically significant regression coefficients of a  
22 multiple regression of first two dimensions of the MDS against the  
23 physical variables. The points are coloured to indicate their cluster  
24 membership.  
25  
26

Table 1. List of physical covariates used in the sample design and regression analyses.

Physical covariate	Definition
BATHY	Seabed depth
DEM4_SLOPE	Slope of the seabed
CARS_NO3_AV	Average nitrate levels
CARS_NO3_SD	Standard deviation of the average nitrate concentration
CARS_O2_AV	Average oxygen concentration
CARS_O2_SD	Standard deviation of the average oxygen concentration
CARS_PO4_AV	Average concentration
CARS_PO4_SD	Standard deviation of the average phosphate concentration
CARS_SI_AV	Average silicate concentration
CARS_SI_SD	Standard deviation of the average silicate concentration
CARS_S_AV	Average salinity
CARS_S_SD	Standard deviation of the average salinity
CARS_T_AV	Average temperature
CARS_T_SD	Standard deviation of the average temperature
M_BSTRESS	Seabed current stress
GA_CRBNT	Sediment carbonate concentration
GA_MUD	Percentage of mud in the sediment
GA_SAND	Percentage of sand in the sediment
GA_GRAVEL	Percentage of gravel in the sediment
SW_CHLA_YAV	Annual average chlorophyll a concentration (as estimated from SeaWifs satellite)
SW_CHLA_YSD	Standard deviation of the average chlorophyll a concentration (as estimated from SeaWifs satellite)
SW_K490_YAV	Annual average turbidity (K490 as estimated from SeaWifs satellite)
SW_K490_YSD	Standard deviation of the annual turbidity y (K490 as estimated from SeaWifs satellite)
SW_K_B_IRR	Benthic irradiance at the seabed
TRWL_EFF_I	Trawling effort index

Table 2. Categories of substrate and epibenthos used in classifying the realtime towed underwater video footage.

Substrate	Epibenthos
Mud	Alcyonarians
Silt	Whips
Sand	Gorgonians
Coarse sand	Sponge
Sand dunes	Hard coral
Rubble	Bivalve bed
Stones	Tube polychaete bed
Rocks	Squid eggs
Reef	Bioturbated seabed
	Live reef
	Algae
	Seagrass

Table 3. Overall total and mean sampling rates ( $\text{kg}\cdot\text{ha}^{-1}$ ) for the major Phyla by sled and trawl indicating relative composition and relative catchability. Ratio is the ratio of the mean trawl sampling rate relative to that of the sled.

Group	Sled		Trawl		Ratio
	Total Wt ( $\text{kg}\cdot\text{ha}^{-1}$ )	Mean ( $\text{kg}\cdot\text{ha}^{-1}$ )	Total Wt ( $\text{kg}\cdot\text{ha}^{-1}$ )	Mean ( $\text{kg}\cdot\text{ha}^{-1}$ )	
Porifera	19,078	114.93	1,239	10.50	0.09
Cnidaria	6,165	37.14	393	3.14	0.08
Chlorophyta	4,733	28.50	2	0.03	0.00
Echinodermata	4,326	26.06	415	2.90	0.11
Ascidiacea	4,138	24.93	75	0.74	0.03
Mollusca	1,783	10.74	198	1.35	0.13
Rhodophyta	1,512	9.11	1	0.07	0.01
Phaeophyta	1,341	8.08	1	0.03	0.00
Bryozoa	656	3.95	8	0.17	0.04
Arthropoda	273	1.64	416	2.83	1.73
Magnoliophyta	267	1.61	1	0.04	0.02
Annelida	206	1.24	1	0.02	0.02
Actinopterygii	178	1.07	1,718	11.69	10.93
Nemertea	64	0.38	-	-	-
Chondrichthyes	2	0.01	261	4.74	474.00
TOTAL	44,722		4,724		

Table 4. Pearson correlation coefficients of Gower dissimilarity matrices among all sites sampled with all 3 gears (trawl, sled and video; n=107 sites).  $R^2$  values are shown in parentheses. \* =  $P < 0.0001$ .

	Combined	Trawl	Sled	Video
Combined	1.00			
Trawl	0.805* (0.65)	1.00		
Sled	0.852* (0.73)	0.383* (0.15)	1.00	
Video	0.536* (0.29)	0.432* (0.19)	0.446* (0.20)	1.00

Table 5. Cluster diagnostics: Cubic Clustering criterion (CCC) and Pseudo F statistics for K-means clustering of the coarse level habitat data.

Number of clusters	CCC	Pseudo F
3	2.66	65.3
4	0.37	60.7
5	-0.17	56.7
6	-1.43	50.3
7	2.31	57.7
8	1.51	53.2
9	2.18	53.1
10	3.04	53.7
11	3.93	54.5
12	3.16	51.2
13	3.25	50.3
14	5.15	54.1
15	4.46	51.3

Table 6. Regression coefficients for the significant and almost significant covariates for a regression of the first two dimensions of an MDS of the coarse level habitat data on the physical covariates.

Covariate	Dimension 1		Dimension 2	
	Coefficient	Pr(> t )	Coefficient	Pr(> t )
BATHY	-4.4491	<0.0001	-0.4536	0.7366
M_BSTRESS	-0.1394	<0.0001	-0.0148	0.6960
GA_GRAVEL	-4.3380	<0.0001	0.4601	0.7740
GA_MUD	5.9100	<0.0001	2.4300	0.0772
SW_K490_YAV	-0.0062	0.3620	0.0123	0.0985
SW_K490_YSD	-0.0034	0.0177	0.0012	0.4121
TRWL_EFF_I	1.8076	<0.0010	0.5869	0.7352

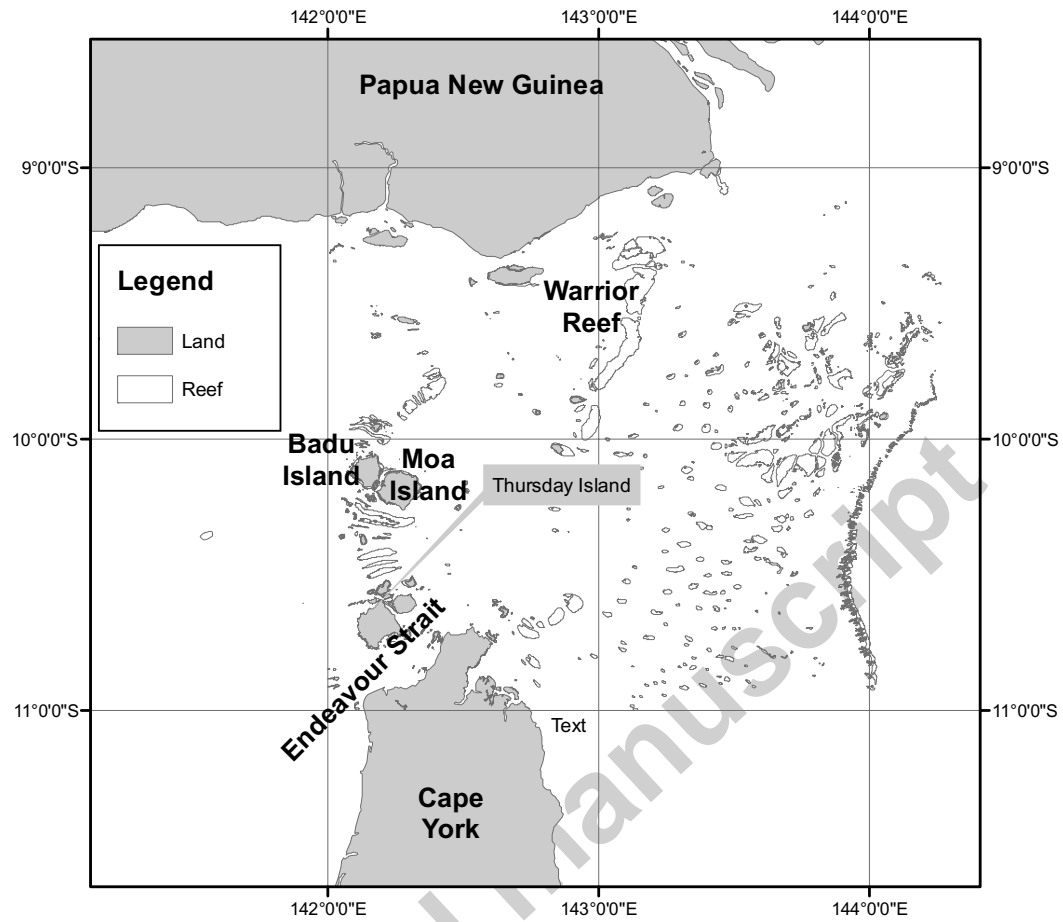


Figure 1. Torres Strait – Map showing the study area.

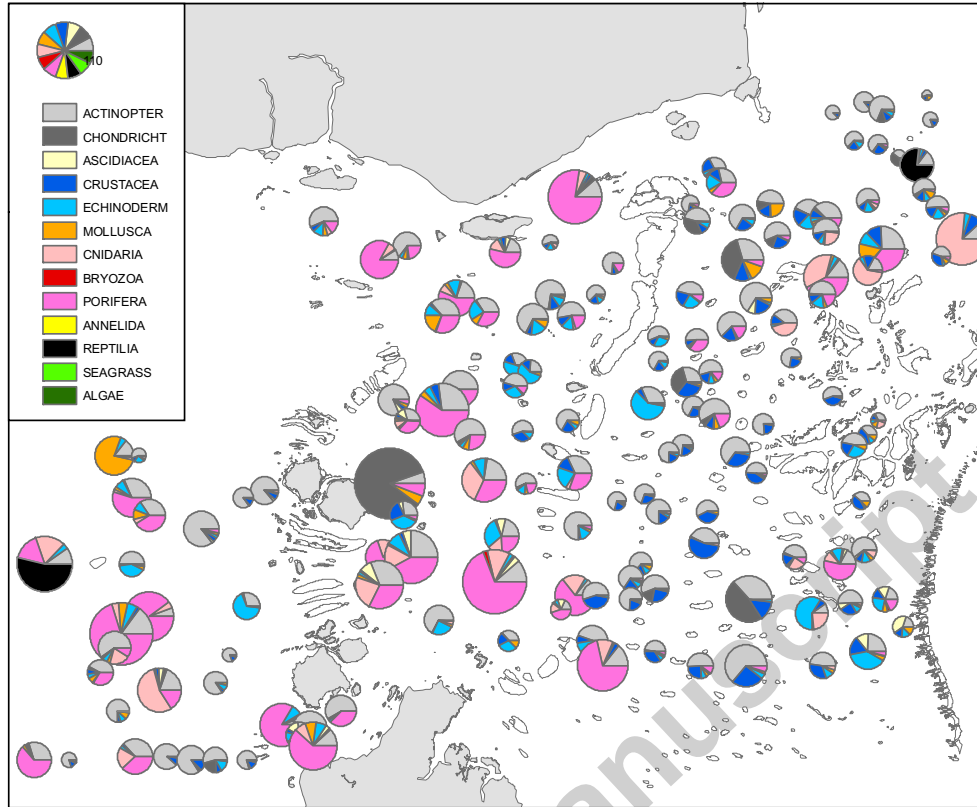


Figure 2. Distribution and abundance of classes of catch from the prawn trawl. The area of each bubble is proportional to the total catch rate ( $\text{kg}\cdot\text{ha}^{-1}$ ). Echinoderm = Echinodermata, Actinopter = Actinopterygii, Chondricht = Chondrichthyes.

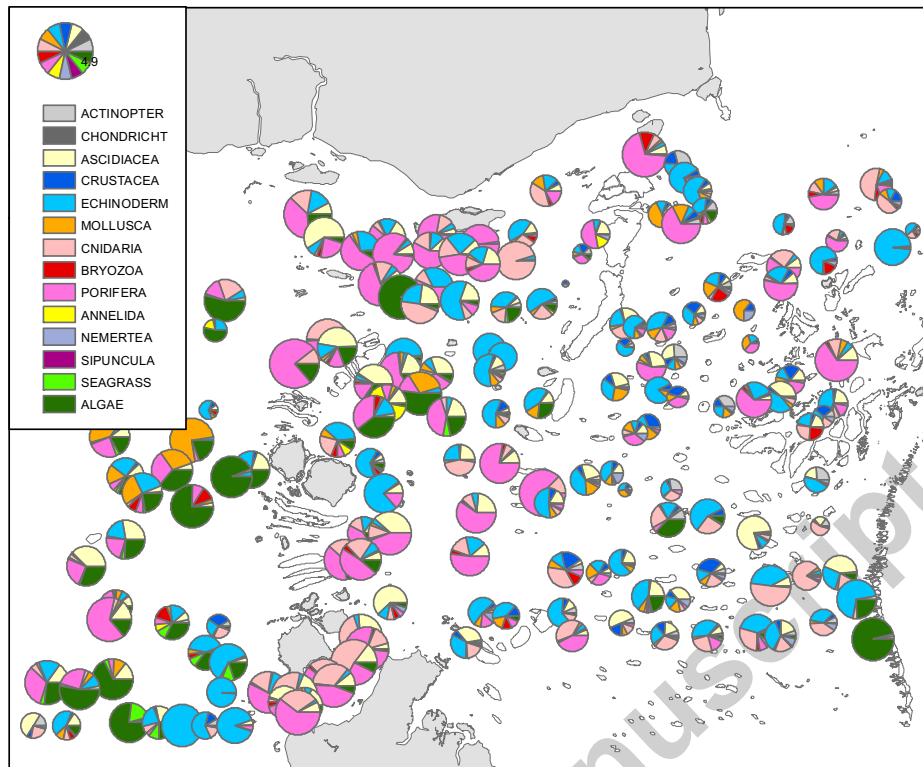


Figure 3. Torres Strait – Catch rates from the benthic sled collected by the F.R.V. James Kirby during February to March 2005. The area of each bubble is proportional to the log of the catch rate ( $\text{kg.ha}^{-1}$ ). Echinoderm = Echinodermata, Actinopter = Actinopterygii.

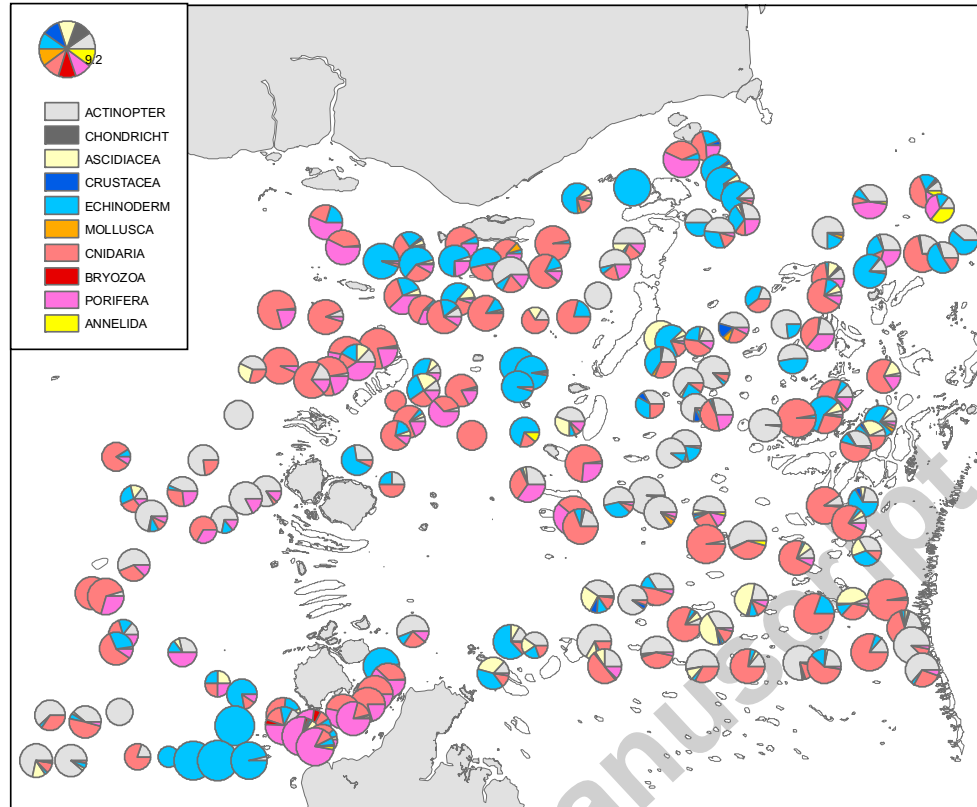


Figure 4. Torres Strait – density of epibenthos observed on the towed underwater video collected by the F.R.V. James Kirby during February to March 2005. The area of each bubble is proportional to the log of the count.ha<sup>-1</sup>. Echinoderm = Echinodermata, Actinopter = Actinopterygii, Chondricht = Chondrichthyes.

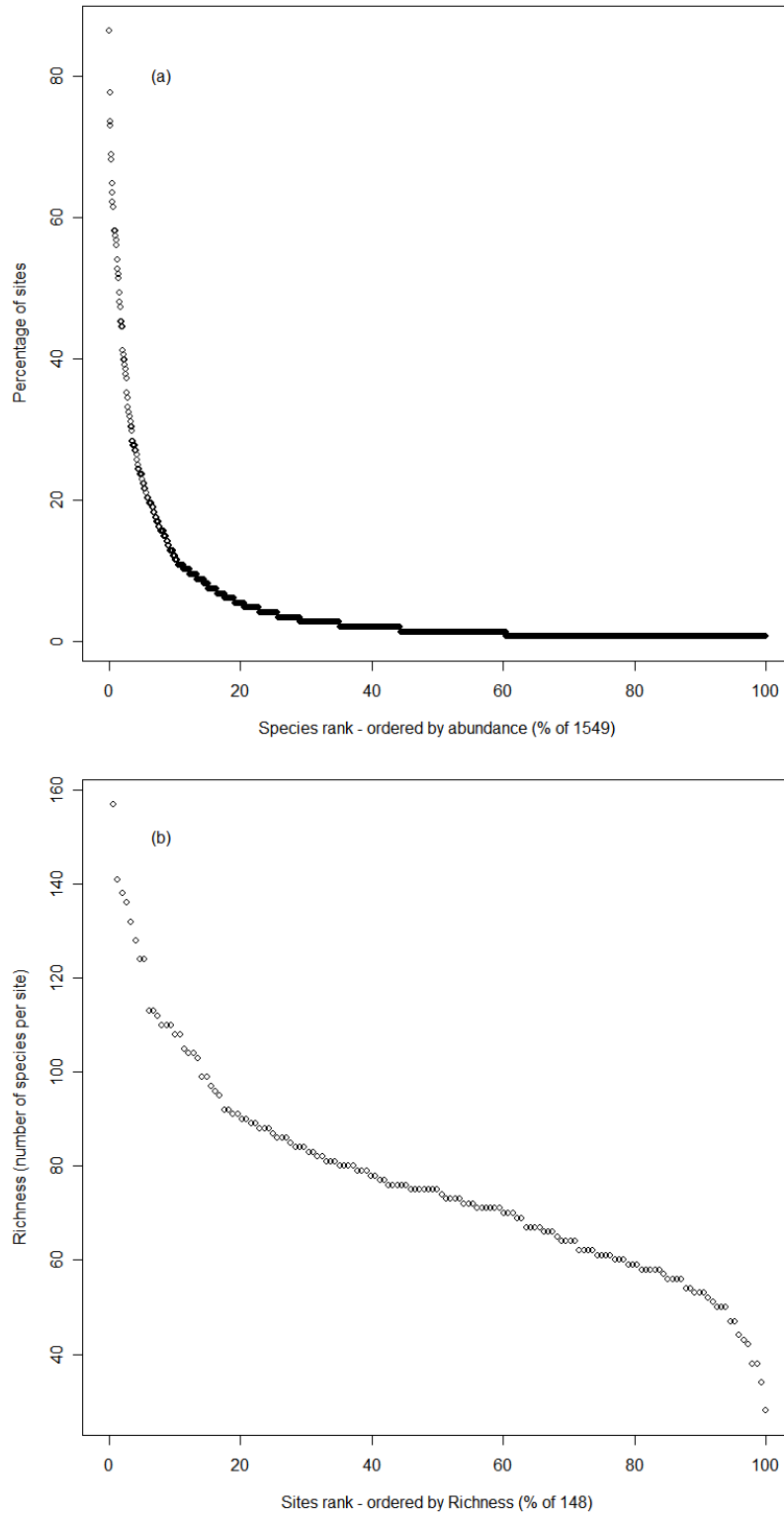


Figure 5. Patterns of (a) prevalence and (b) richness of 1549 OTUs at 148 Trawl sites.

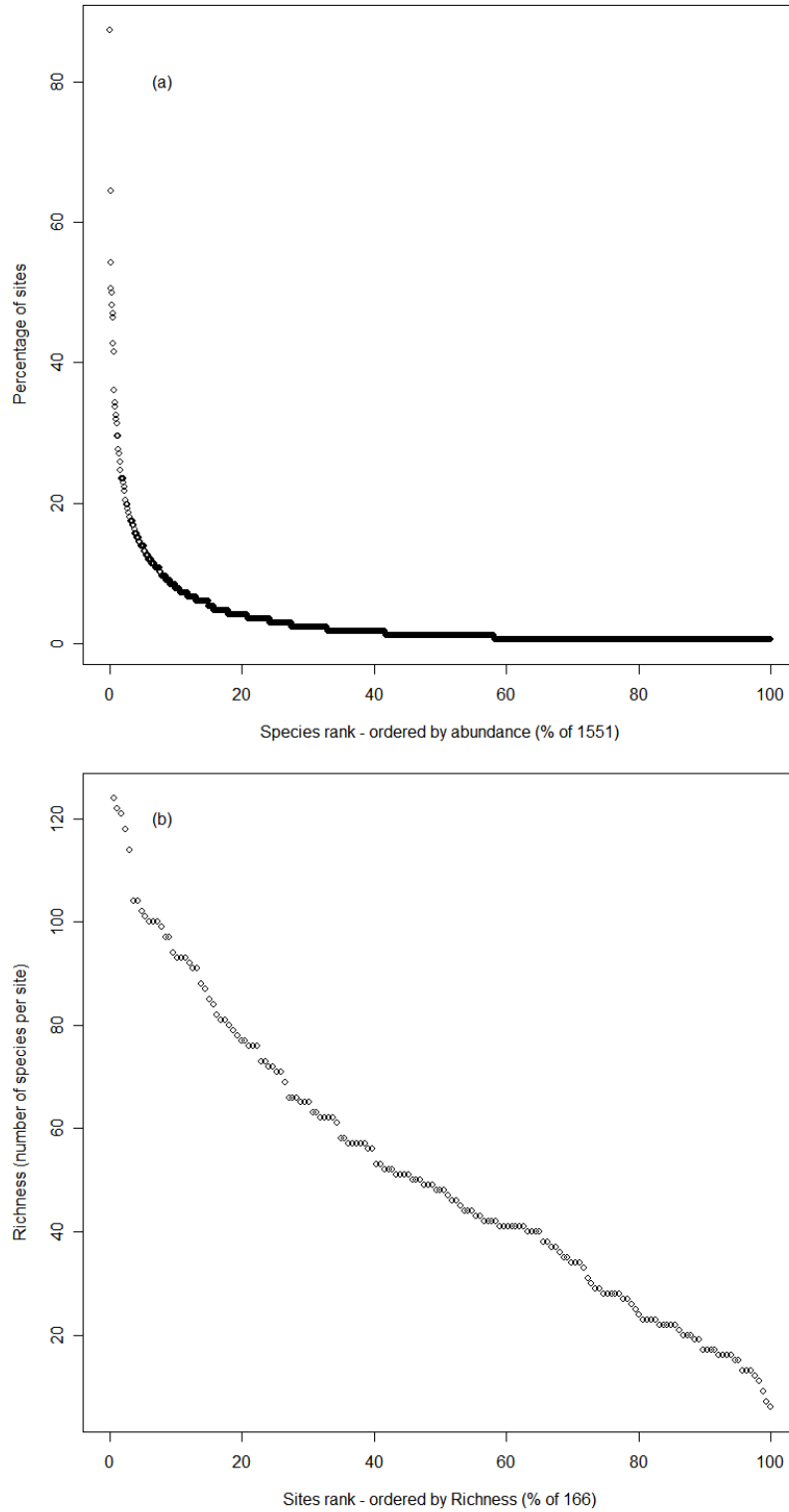


Figure 6. Patterns of (a) prevalence and (b) richness of 1551 OTUs at 166 sled sites.

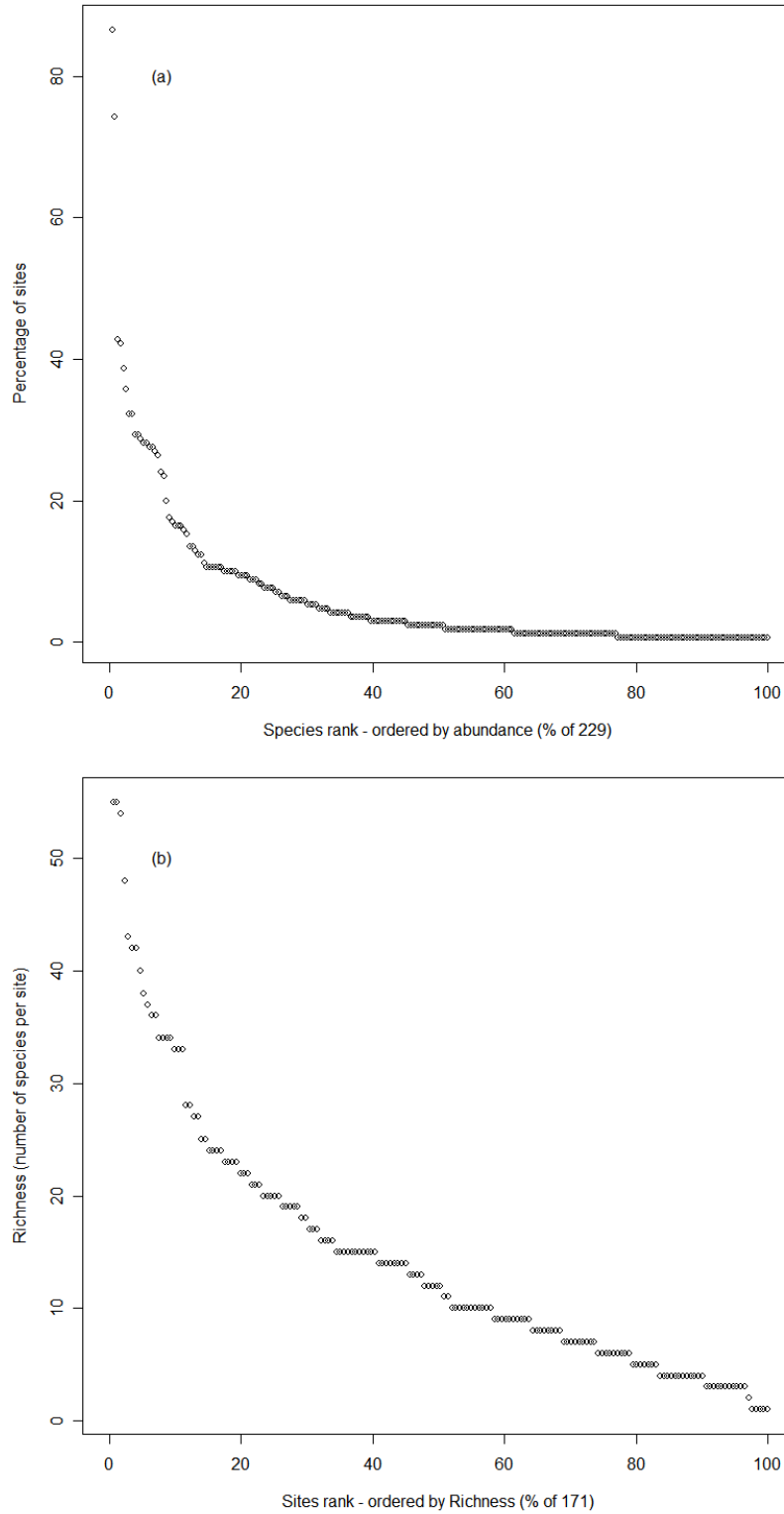


Figure 7. Patterns of (a) prevalence and (b) richness of 229 OTUs at 171 video sites.

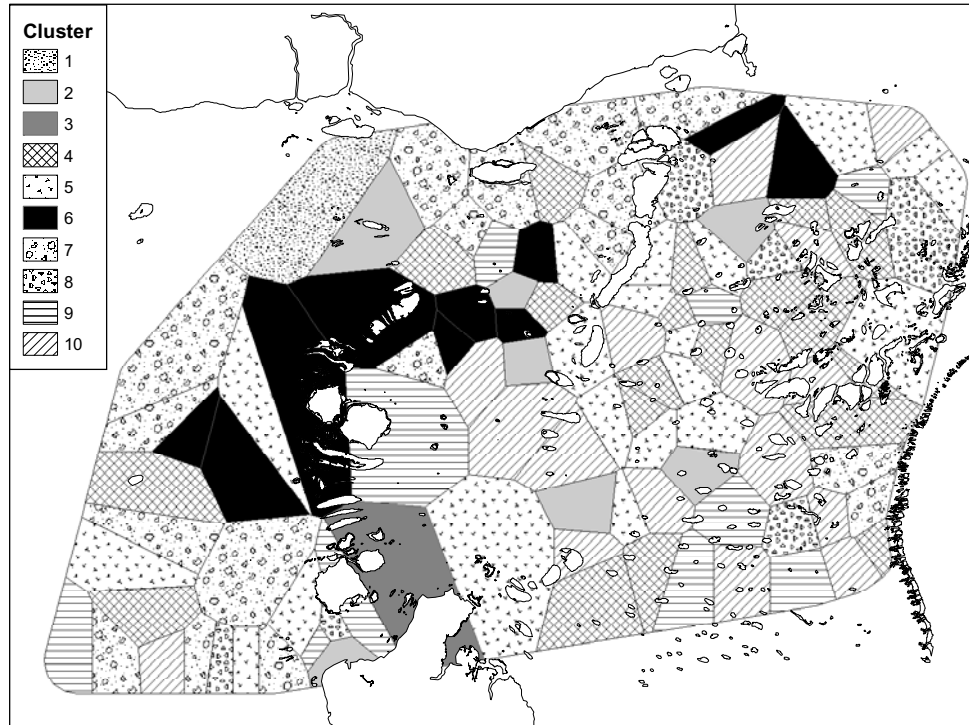


Figure 8. Torres Strait – voronoi mapping of the benthic assemblages identified by hierarchical clustering of the combined trawl, sled and video data.

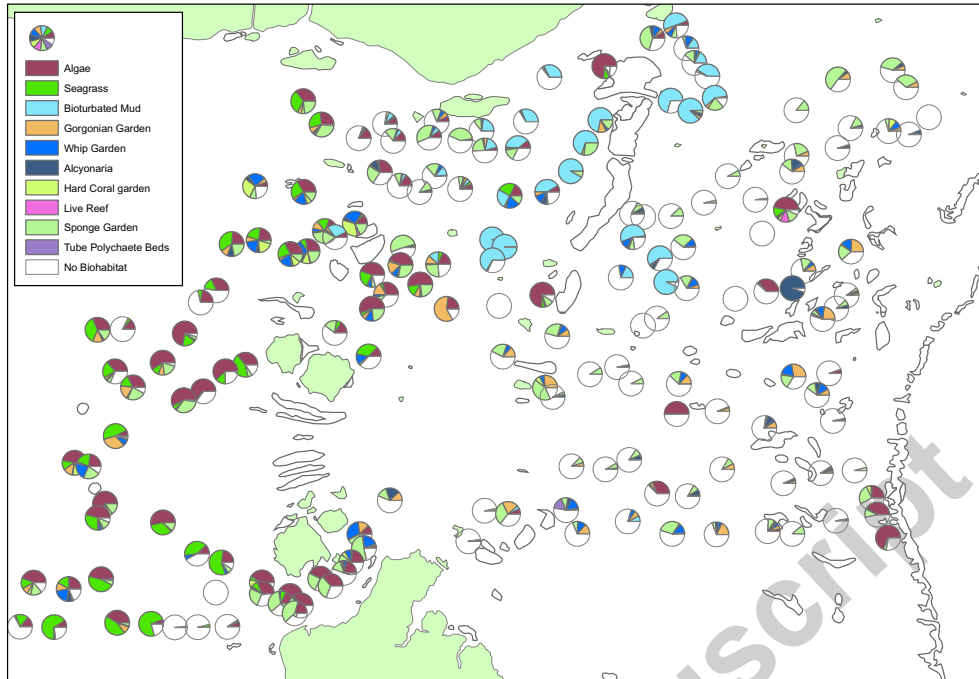


Figure 9. Torres Strait – Distribution of major classes of epibenthos identified from towed underwater video taken during the second survey in March-April 2005.

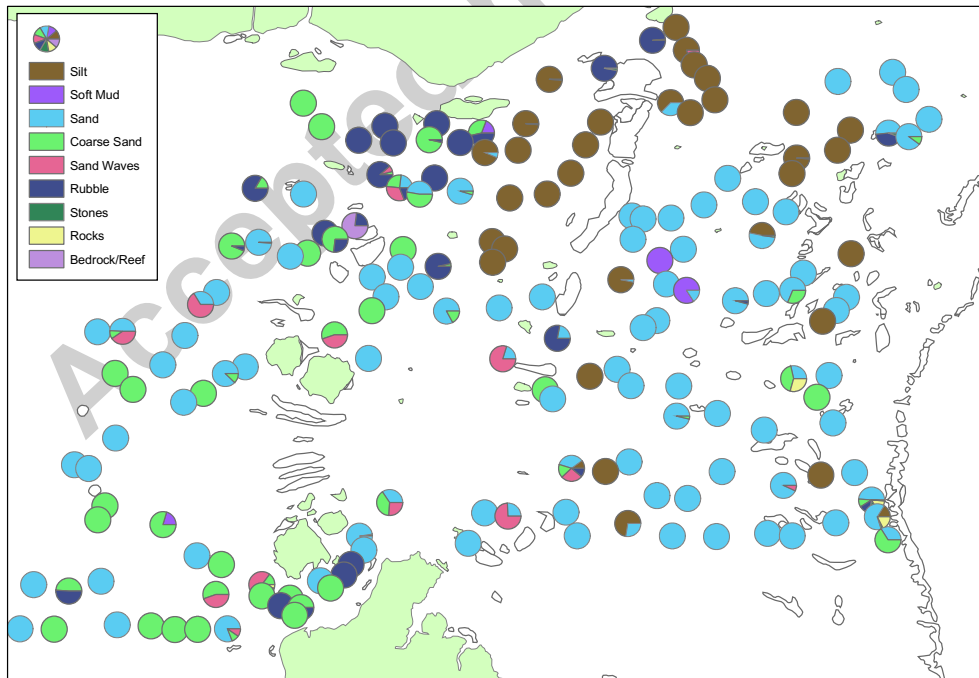


Figure 10. Torres Strait – Distribution of major classes of sediment identified from towed underwater video taken during the second survey in March-April 2005.

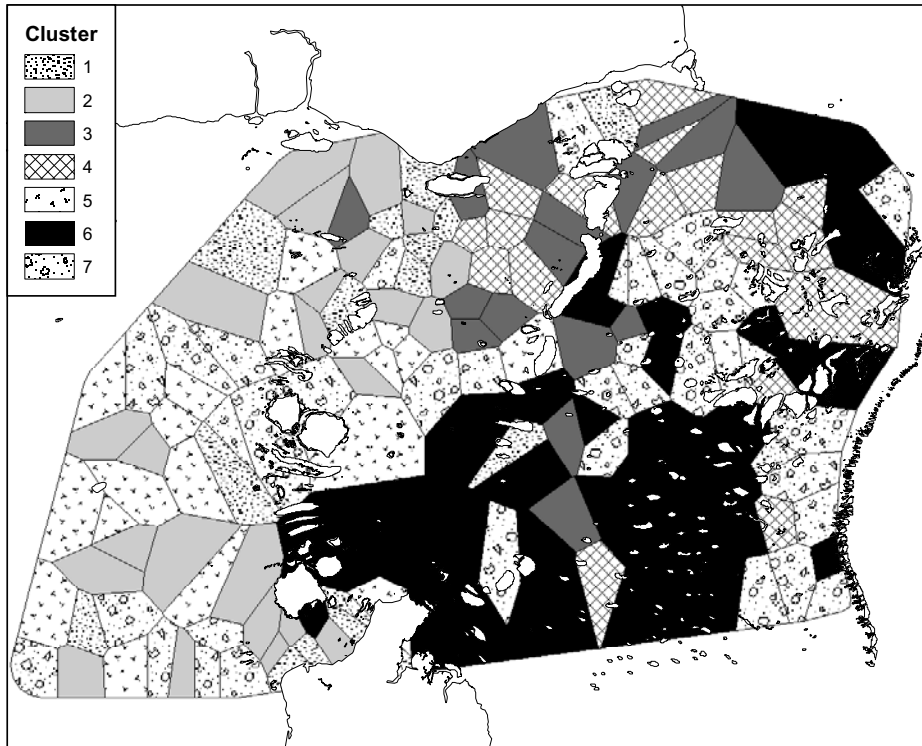


Figure 11. Torres Strait – voronoi mapping of the benthic assemblages identified by K-means clustering of the real-time video data.

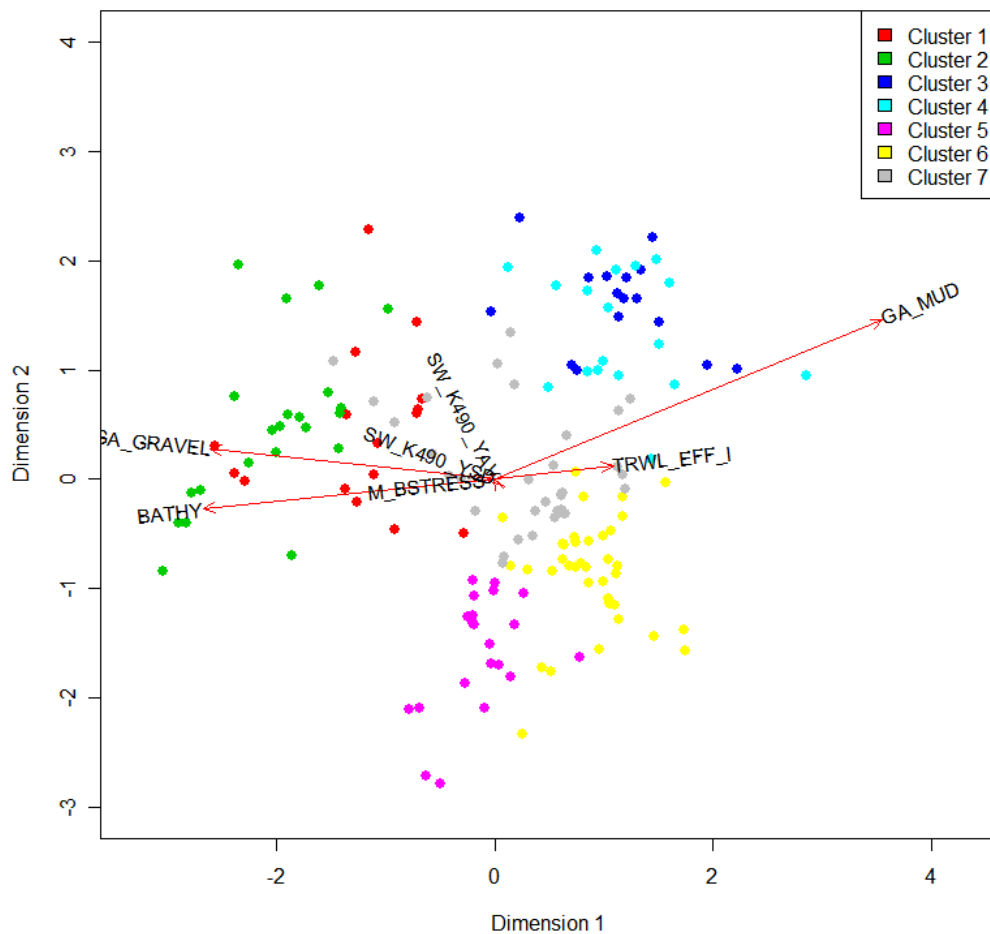


Figure 12. Biplot of the MDS of the coarse-level habitat data with vectors representing the statistically significant regression coefficients of a multiple regression of first two dimensions of the MDS against the physical variables. The points are coloured to indicate their cluster membership.