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

Authors: **Haywood, M.D.E.[1*], Pitcher, C.R.[1], Ellis, N.[1], Wassenberg, T.J.[1], Smith, G.[1], Forcey, K.[1], McLeod, I.[1], Carter, A.[2], Strickland, C.[3], Coles, R..**

[1] CSIRO Division of Marine and Atmospheric Research, PO Box120, Cleveland Qld. 4163, Australia.

[2] Northern Fisheries Centre, Department of Primary Industries and Fisheries, PO Box 5396, Cairns, Qld., 4810, Australia.

[3] Queensland Museum, PO Box 3300, South Bank, Qld. 4101, Australia.

***Corresponding author, CSIRO Division of Marine and Atmospheric Research, PO Box 120, Cleveland Qld. 4163, Australia.**

phone: 61+ 7 3826 7224 fax: 61+ 7 3826 7222 email: mick.haywood@csiro.au

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Abstract

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

Keywords: Seafloor mapping, benthic environment, aquatic communities, underwater video, Australia, Queensland, Torres Strait

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Introduction

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

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

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

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

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

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

Materials and Methods

Sample design

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

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

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

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

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

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

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[1] 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

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

Field sampling

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

Trip 1: Trawl sampling

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

After field sampling, in laboratories, frozen samples were thawed and identified to species if possible, weighed and recorded. If identification to species was not possible, morphologically distinct taxa were grouped to Operational Taxonomic Unit (OTU). Reference specimens of all OTUs were retained.

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Trip 2: Video transects and Epibenthic Sled sampling

Description of the sampling devices

1. *Drop camera*

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

2. *Epibenthic sled*

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

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Sampling procedures

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

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

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

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

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

Data analysis

Trawl and sled samples

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

Quantification of epibenthos from U/W video

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

Comparison of biodiversity information obtained from different gear types

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

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as small fish and crustaceans whereas the sled is efficient at capturing sessile epibenthos. To compare the biodiversity information content obtained from these three methods, Gower dissimilarity matrices (Gower, 1971) among all sites sampled with all three devices were computed (based on $\log_e(x + 1)$ transformed biomass for sled and trawl data and $\log_e(x + 1)$ transformed count data from the video). Dissimilarity matrices were computed for all 3 devices pooled (this was considered to be the benchmark dataset) and for each device separately.

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

Assemblage characterisation using data from trawl, sled and video

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

Characterisation of seabed habitats from U/W video

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

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

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

Results

One thousand five hundred and fifty-one OTUs (”species”) were sampled by the epibenthic sled from 167 sites, 1549 in the trawl from 148 sites and 229 were identified from the video from 173 sites. Of these, only 14 species were identified in all three gear types and 728 were caught by both sled and trawl. Many of these were caught more effectively by one gear than by the other; e.g. the bryozoan *Adeonella* sp. 2 was caught at 69 sites in the sled, but only at a single site in the trawl. Eight hundred and twenty-three of the OTUs were unique to the sled and 824 to the trawl. Comparison at this level with the video data was difficult because only 29 of the 229 OTUs documented from the video were actually identifiable to species level and none of those were uniquely sampled by the video.

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

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

Prawn trawl catches

The catch rates of the prawn trawl were dominated by Actinopterygii and Porifera, catches of Echinodermata, Crustacea and Cnidaria were < one third of those of the Actinopterygii (Table 3). Catch rates of the other groups were very low. Actineroptygii were caught at all sites by the prawn trawl and catch rates were generally high throughout the strait (Figure 2), similarly the trawl catch rates of echinoderms were ubiquitous through the study area. Crustaceans were also caught throughout the region but catch rates were much greater in the eastern side of the strait, particularly within and to the south of the commercial prawn trawl grounds. In contrast, poriferan catch rates were higher in the western region, although they were also patchier than those of crustaceans in the east (Figure 2).

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

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Benthic sled catches

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

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

Video count data

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

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Species prevalence and richness

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

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

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Comparison of biodiversity information obtained from different gear types

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

Assemblage characterisation using data from trawl, sled and video

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

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

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

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

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Assemblage 4 (n = 19; s = 1008): Characterised principally by a very large amount of Ascidiacea and lesser amounts of Magnoliophyta, Crustacea, Anthozoa, Florideophyceae and Rhodophyceae. Assemblage 4 was widespread, but mostly found in the eastern strait (Figure 8).

Assemblage 5 (n = 20; s = 883): Consisted mainly of Actinopterygii, Phaeophyta, Florideophyceae, Ascidiacea, Crinoidea, Crustacea and Magnoliophyta. Assemblage 5 was common throughout the central and eastern Torres Strait (Figure 8).

Assemblage 6 (n = 10; s = 687): Consisted primarily of Bryopsidophyceae, Ascidiacea, Calcarea, Chlorophyta, Actinopterygii, Demospongiae and Bilvalvia. Assemblage 6 was mostly located in the western and far northern strait (Figure 8).

Assemblage 7 (n = 17; s = 1041): Comprised largely of Crinoidea, Ascidiacea, Anthozoa, Chondrichthyes and Demospongiae. Assemblage 7 was mainly located in the western and far northern strait (Figure 8).

Assemblage 8 (n = 6; s = 613): Consisted mainly of Chondrichthyes, Ascidiacea, Demospongiae, Florideophyceae, Echinoidea and Asteroidea. This assemblage was mainly located in the eastern strait (Figure 8).

Assemblage 9 (n = 10; s = 818): Consisted mainly of Actinopterygii, Florideophyceae, Chondrichthyes, Crustacea, Demospongiae and Asteroidea. This assemblage was widespread throughout the strait (Figure 8).

Assemblage 10 (n = 16; s = 935): Consisted mainly of Actinopterygii, Crustacea, Magnoliophyta, Chlorophyta and Anthozoa. This assemblage was confined to the eastern strait (Figure 8).

Habitat recorded by towed video

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

Identification of habitats – clustering of real-time video data

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

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

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

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

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

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

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

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

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

Relationships between the videoed habitat and physical patterns

Only 7 of the 25 physical covariates were significantly or almost significantly ($p<0.1$) correlated with either of the first two dimensions of the MDS of the coarse-level habitat data. The largest coefficients were in the first MDS dimension for levels of gravel, mud, depth and trawling effort (Table 6). Habitats 3 and 4 were associated with higher levels of mud (GA_MUD) and Habitats 6 and 7 with high levels of trawling effort (TRWL_EFF_I; Figure 12). Habitats 1 and 2 were associated with low levels of current stress, gravel, shallow depths (M_BSTRESS, GA_GRAVEL, BATHY) and to a lesser extent with annual mean and variability of turbidity levels (SW_K40_YAV, SW_K490_YSD). Habitat 5 was not clearly associated with any of the covariates.

Discussion

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

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

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

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

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

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

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

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

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

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

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

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

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

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Table Captions

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

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

Table 3. Overall total and mean sampling rates ($kg.ha^{-1}$) 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.

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.

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

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.

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Figure Captions

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

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 ($kg.ha^{-1}$). Echinoderm = Echinodermata, Actinopter = Actinopterygii, Chondricht = Chondrichthyes.

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

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Figure 6. Patterns of (a) prevalence and (b) richness of 1549 species at 148 Trawl stations.

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

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.

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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

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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 ($kg.ha^{-1}$) 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 ($kg.ha^{-1}$)	Mean ($kg.ha^{-1}$)	Total Wt ($kg.ha^{-1}$)	Mean ($kg.ha^{-1}$)	
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		

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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

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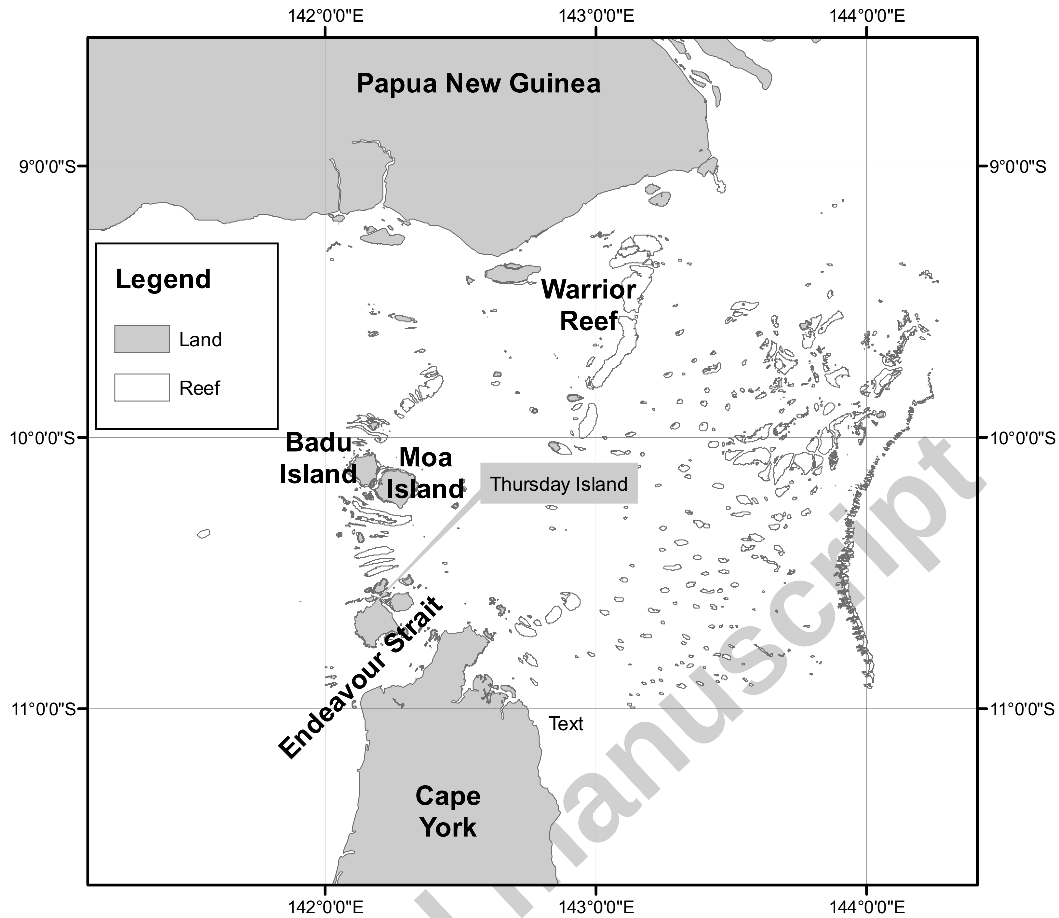

Figure 1. Torres Strait – Map showing the study area.

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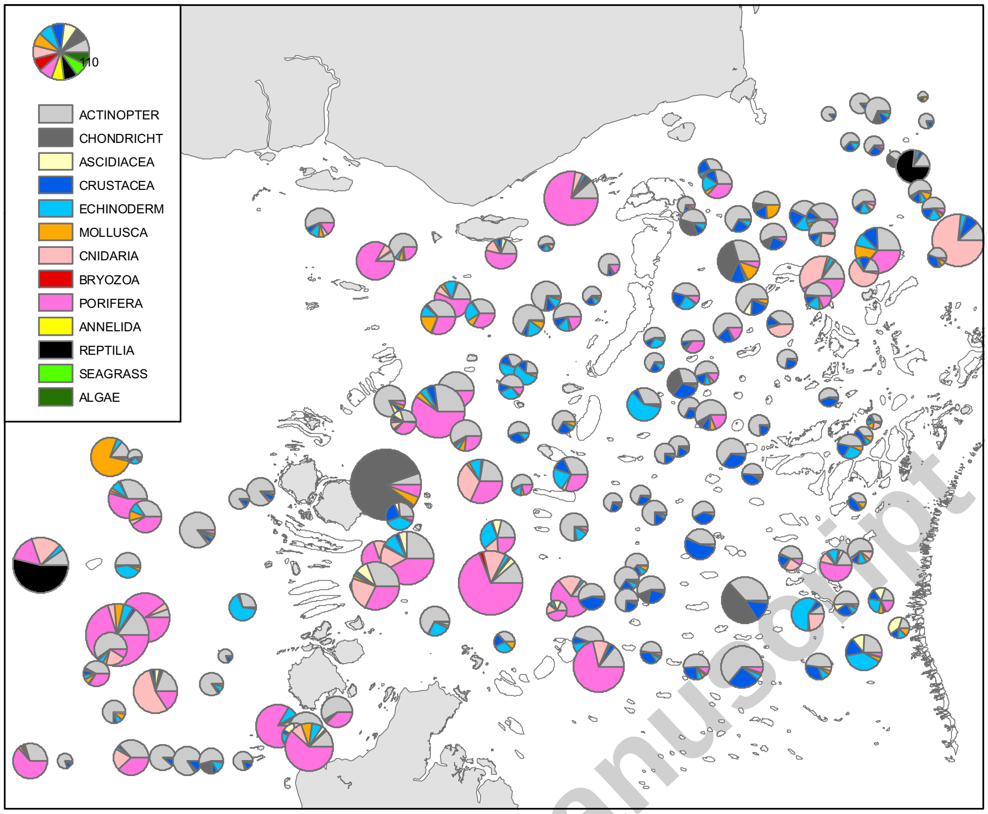

Figure 2. Distribution and abundance of classes of catch from the prawn trawl. The area of each bubble is proportional to the total catch rate (kg.ha^{-1}). Echinoderm = Echinodermata, Actinopter = Actinopterygii, Chondricht = Chondrichthyes.

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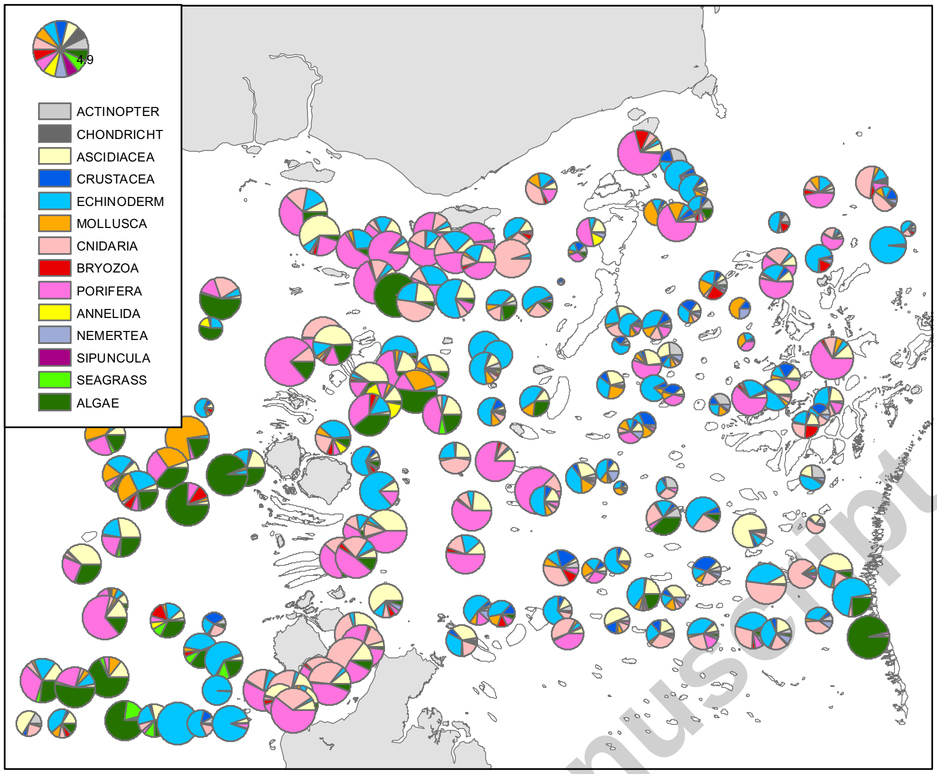

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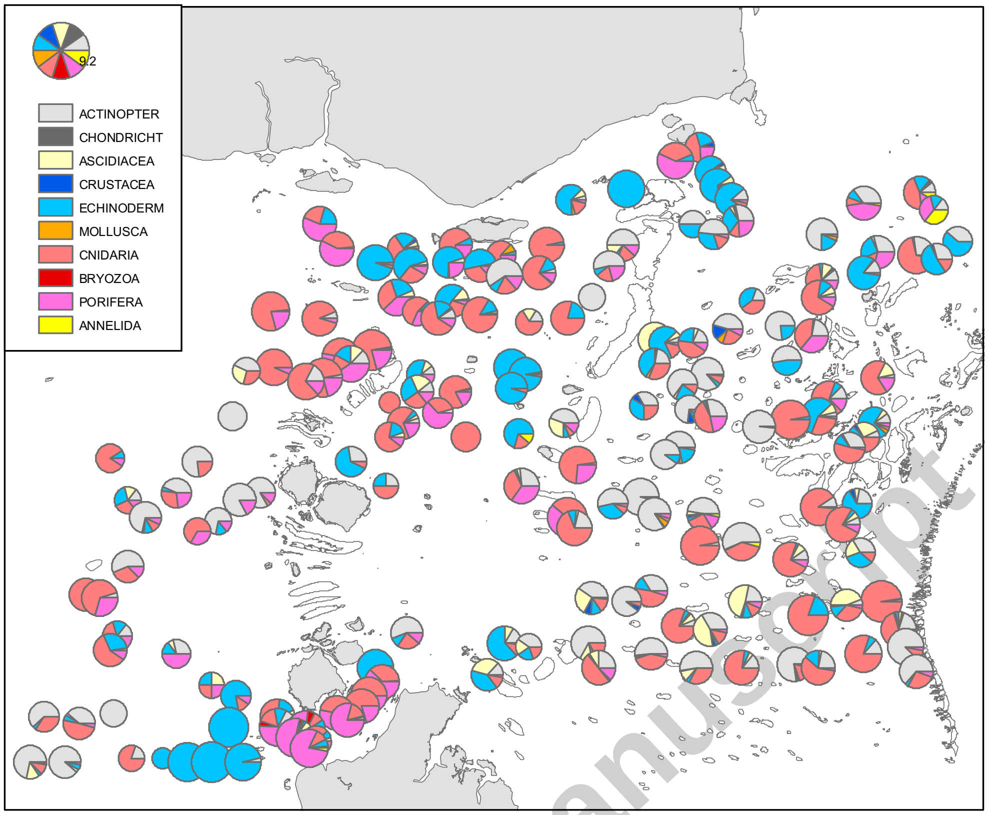

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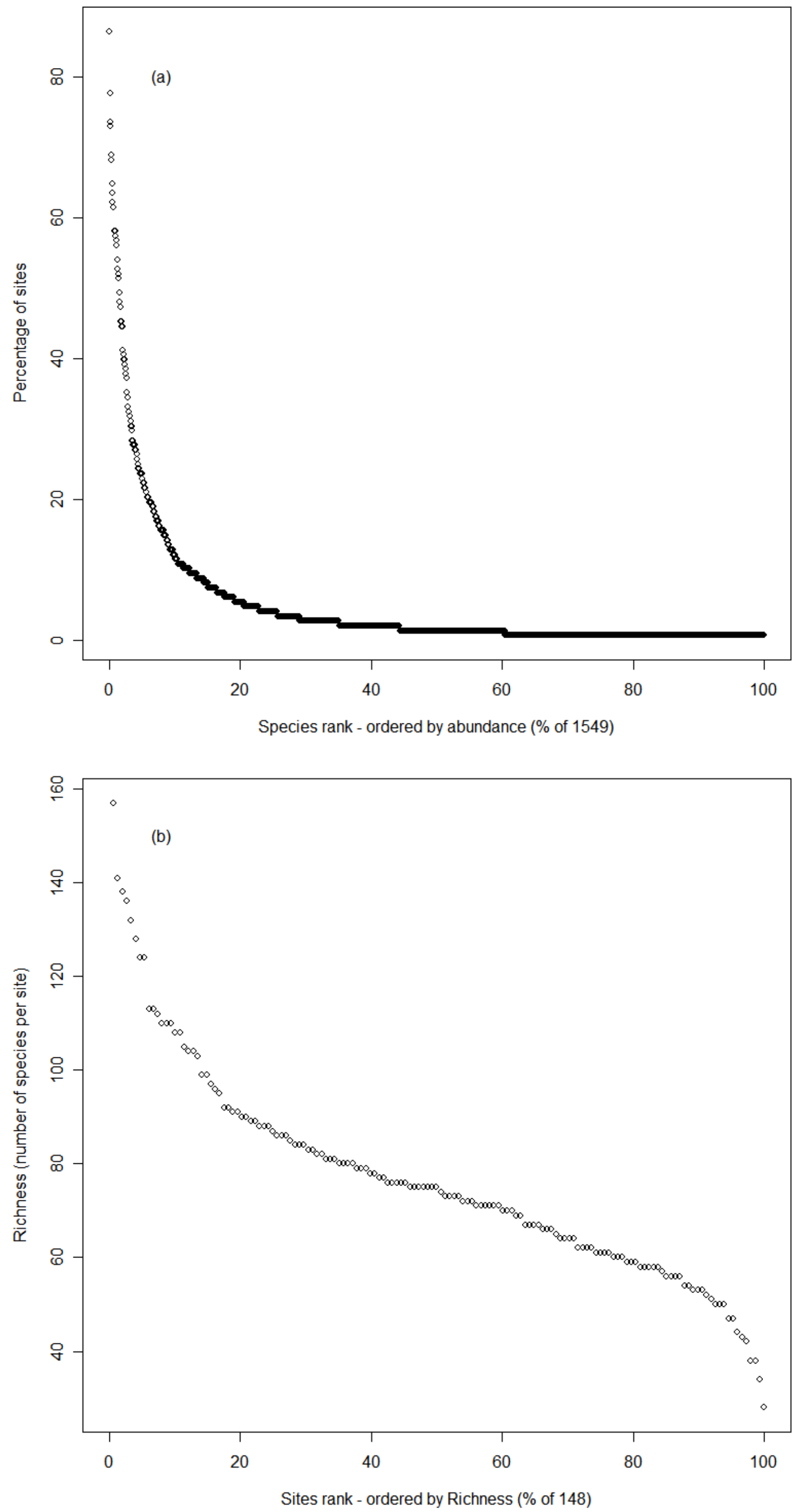

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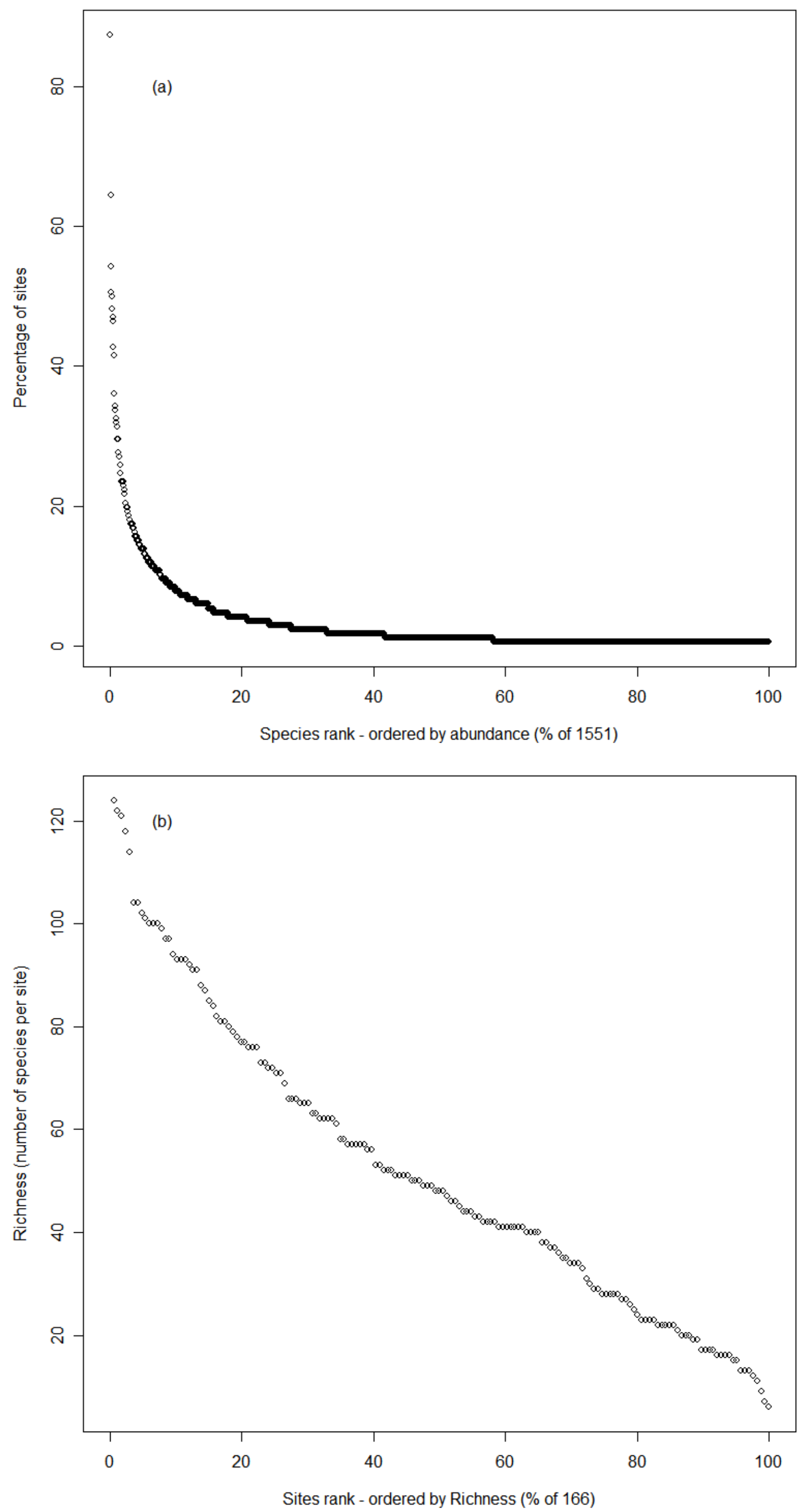

Figure 6. Patterns of (a) prevalence and (b) richness of 1551 OTUs at 166 sled sites.

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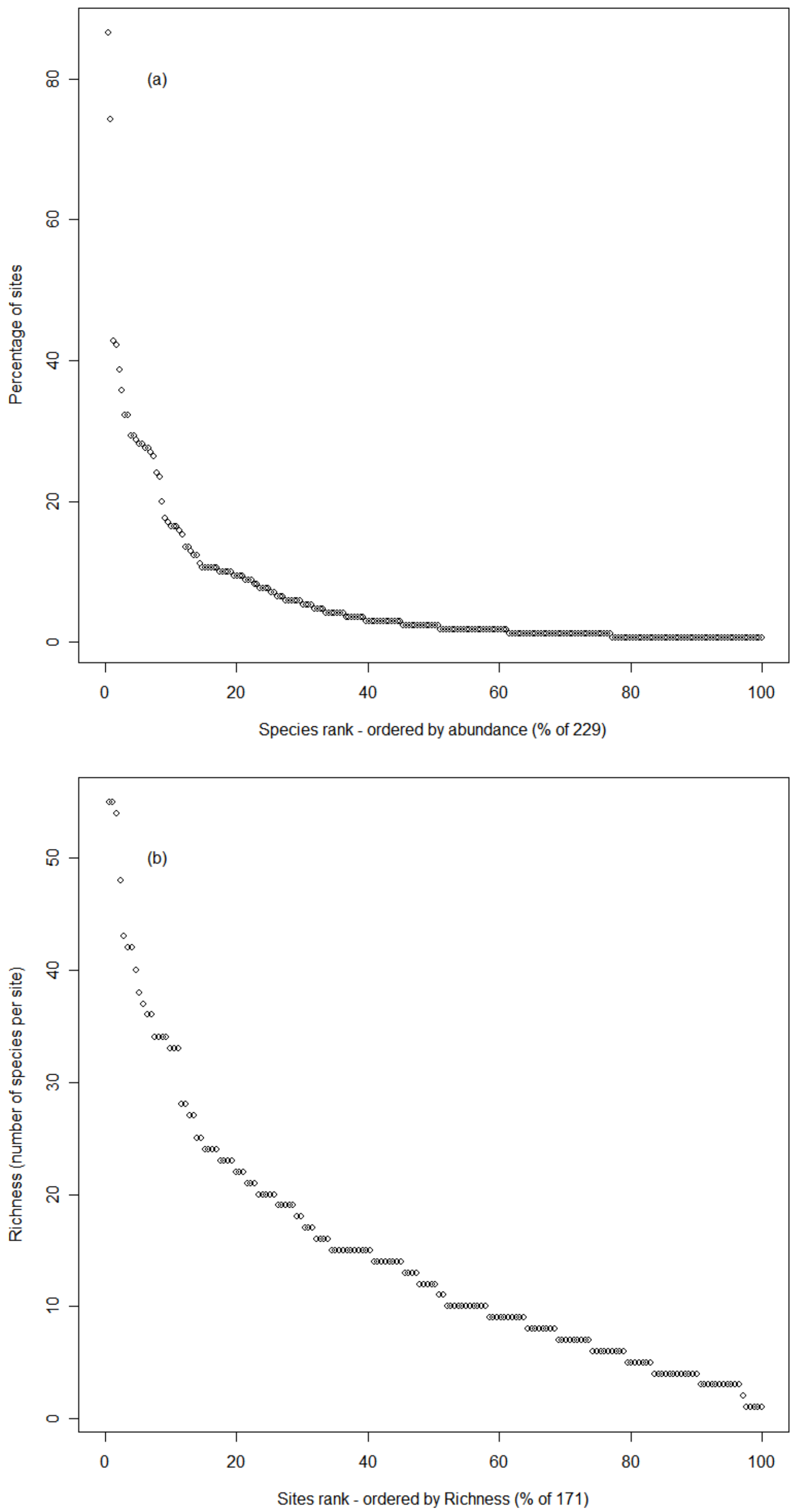

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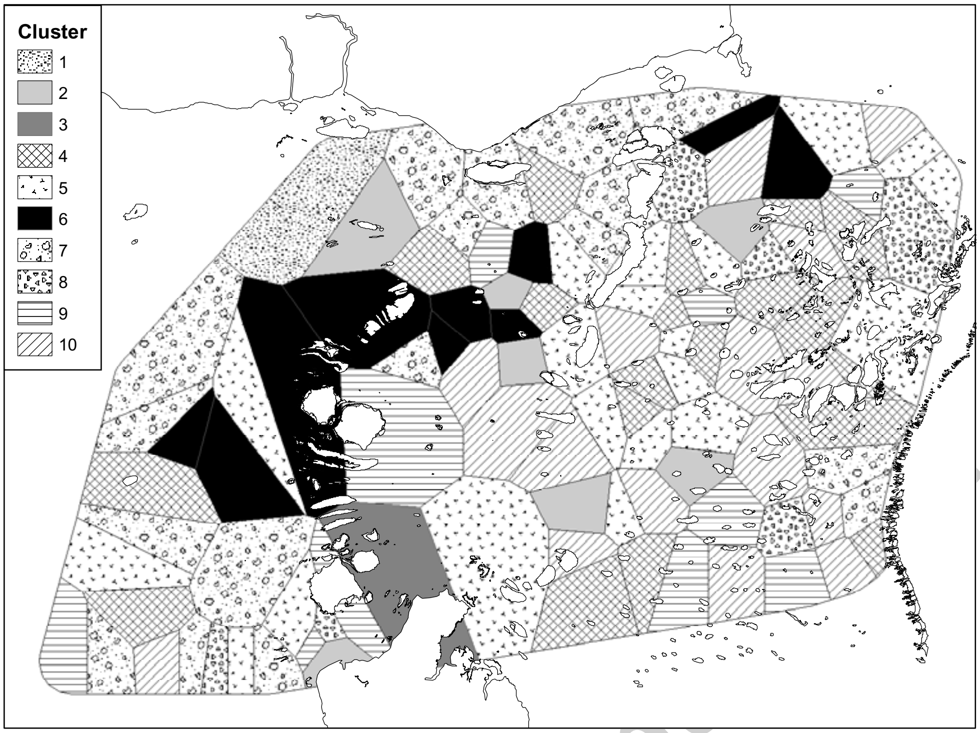

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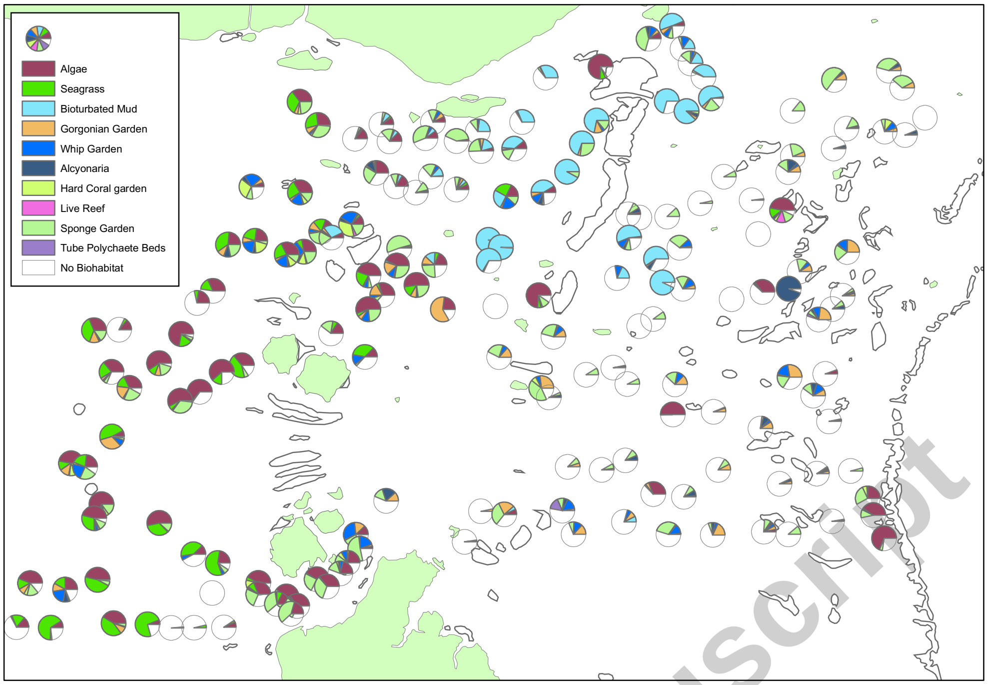

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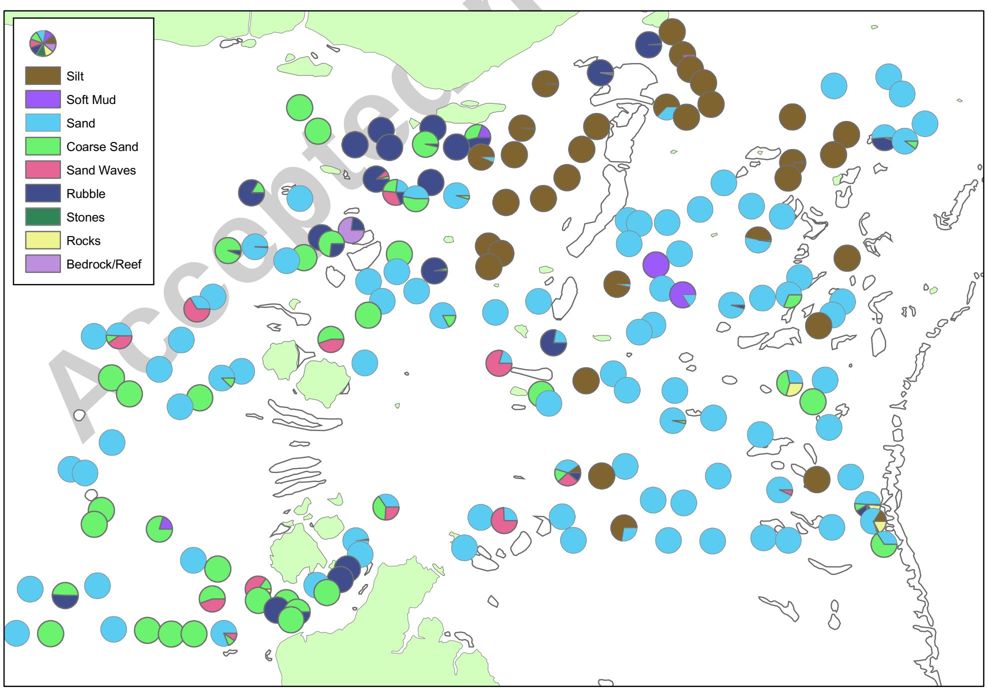

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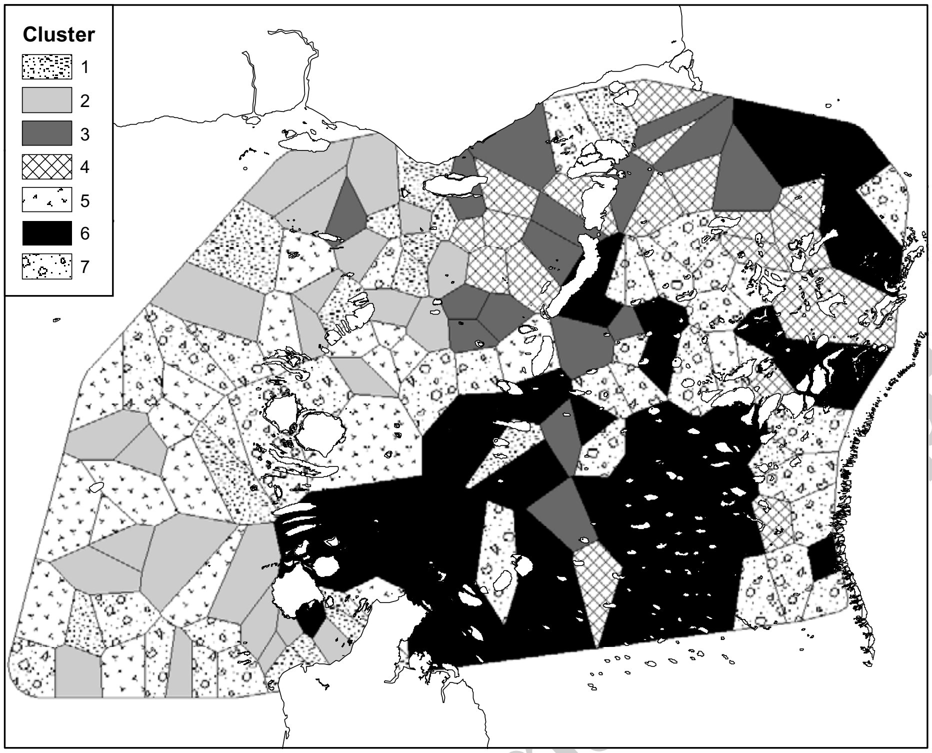

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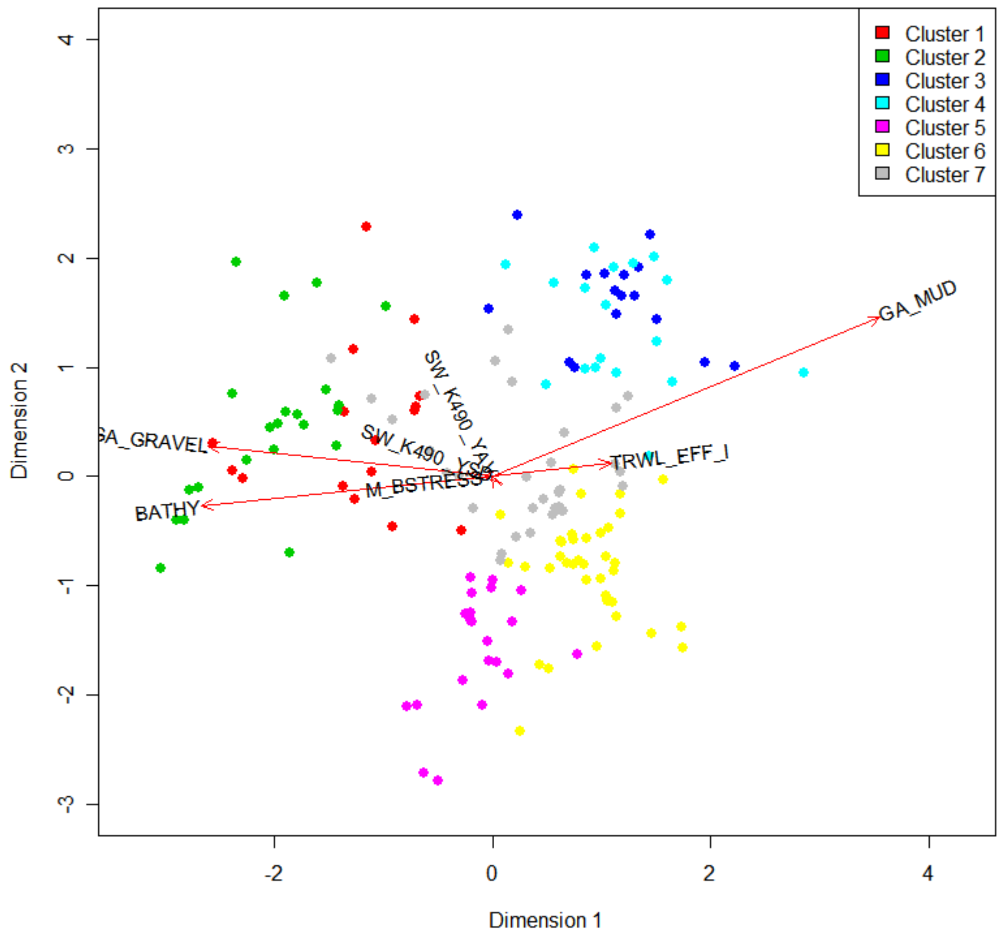

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