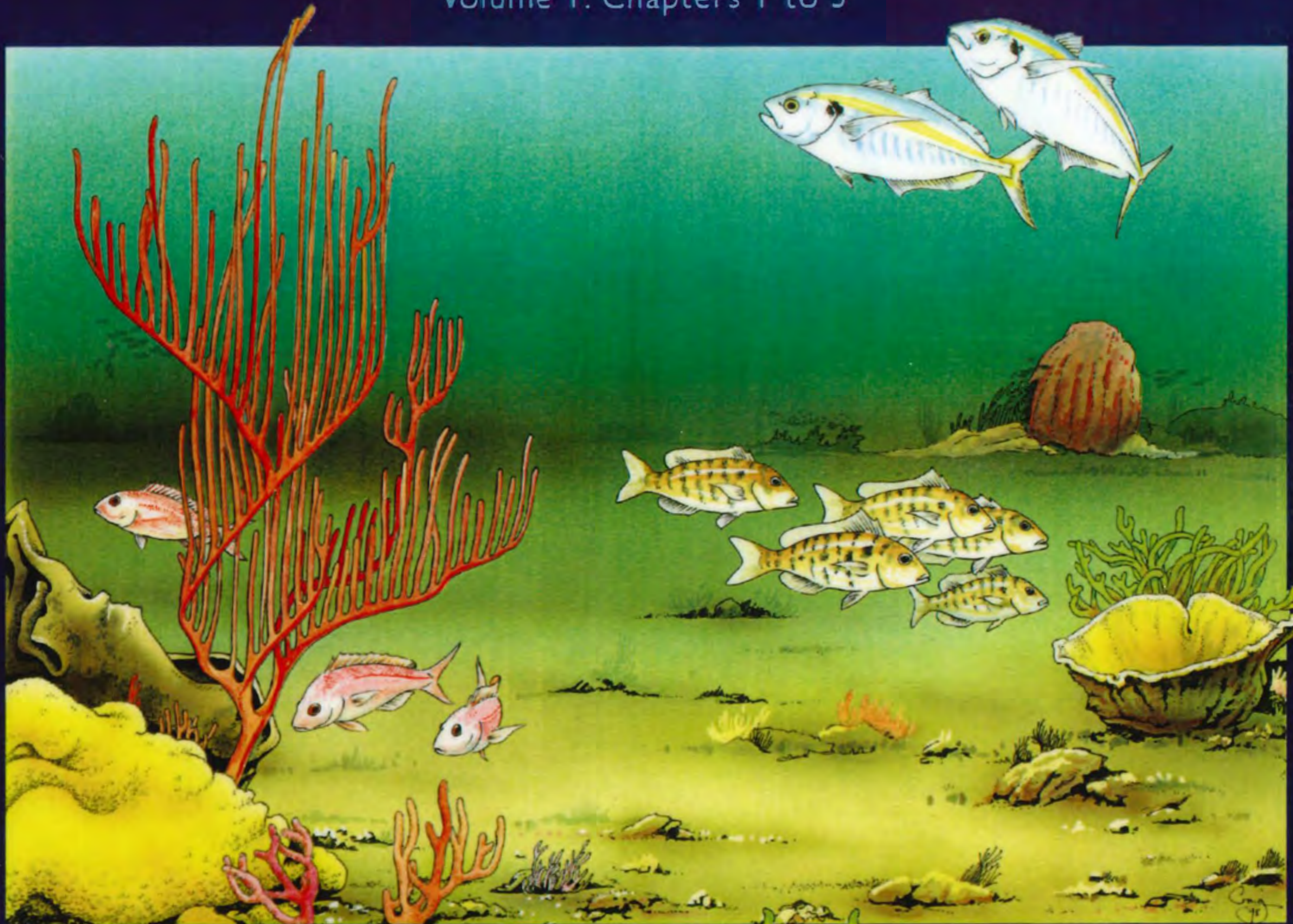
Environmental Effects of Prawn Trawling in the Far Northern Section of Great Barrier Reef: 1991-1996

Volume 1: Chapters 1 to 3



Final report to
Great Barrier Reef
Marine Park
Authority and
Fisheries Research
and Development
Corporation

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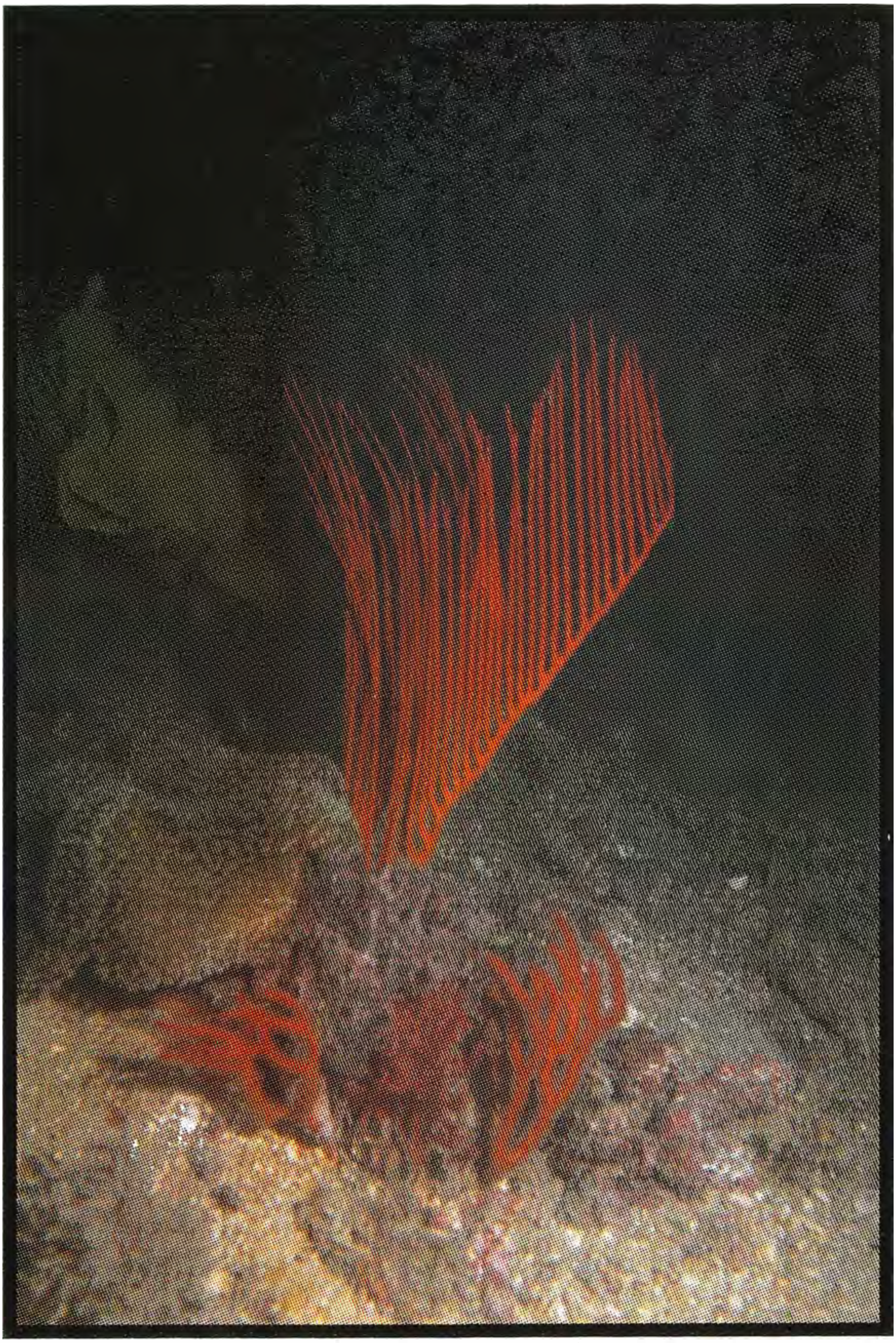


Plate 1. Gorgonians (*Junceella* sp, *Ctenocella* sp), soft coral (*Sarcophyton* sp) and sponge (*Ianthella basta*) in the background.

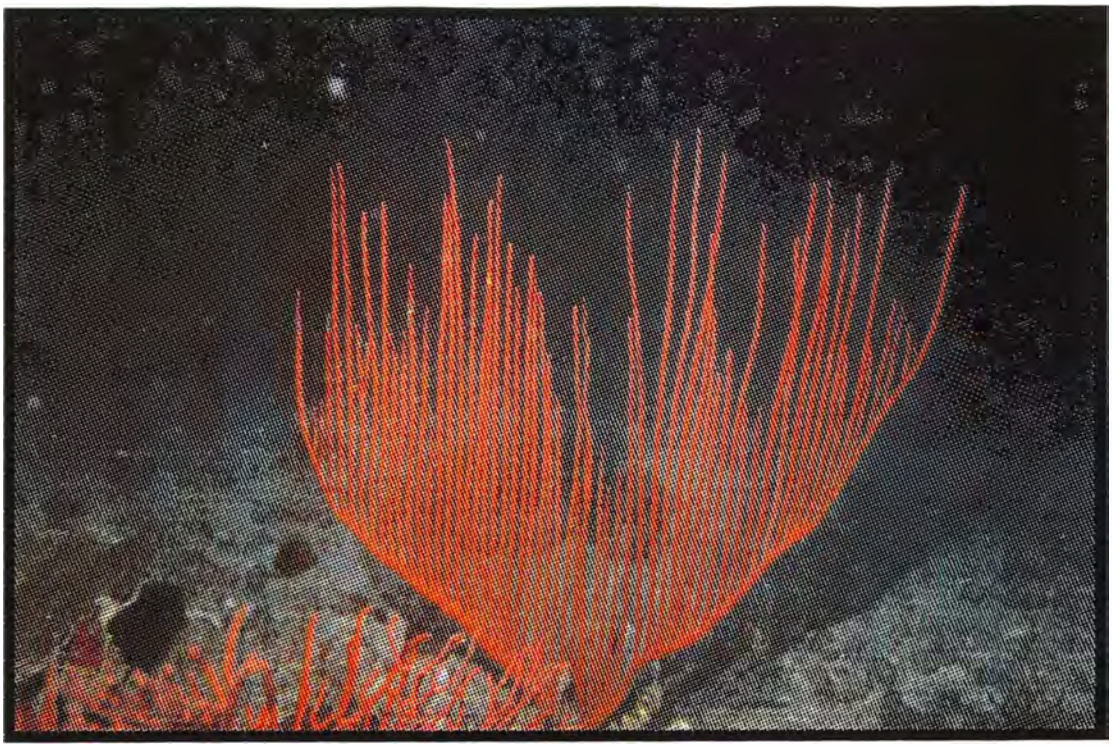


Plate 2. Top - Gorgonian (*Ctenocella pectinata*),
Bottom - Sponge (*Xestospongia* sp).

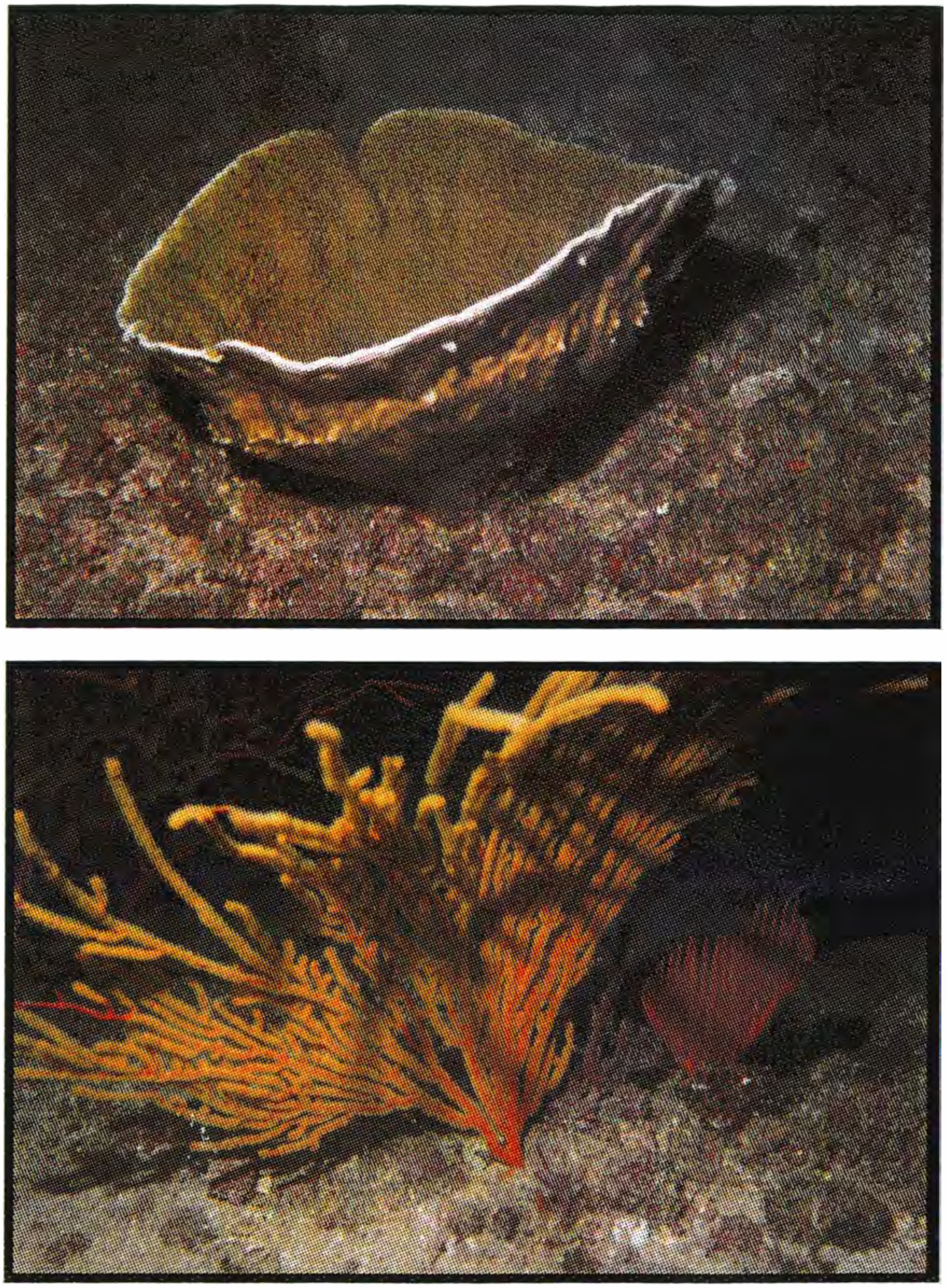
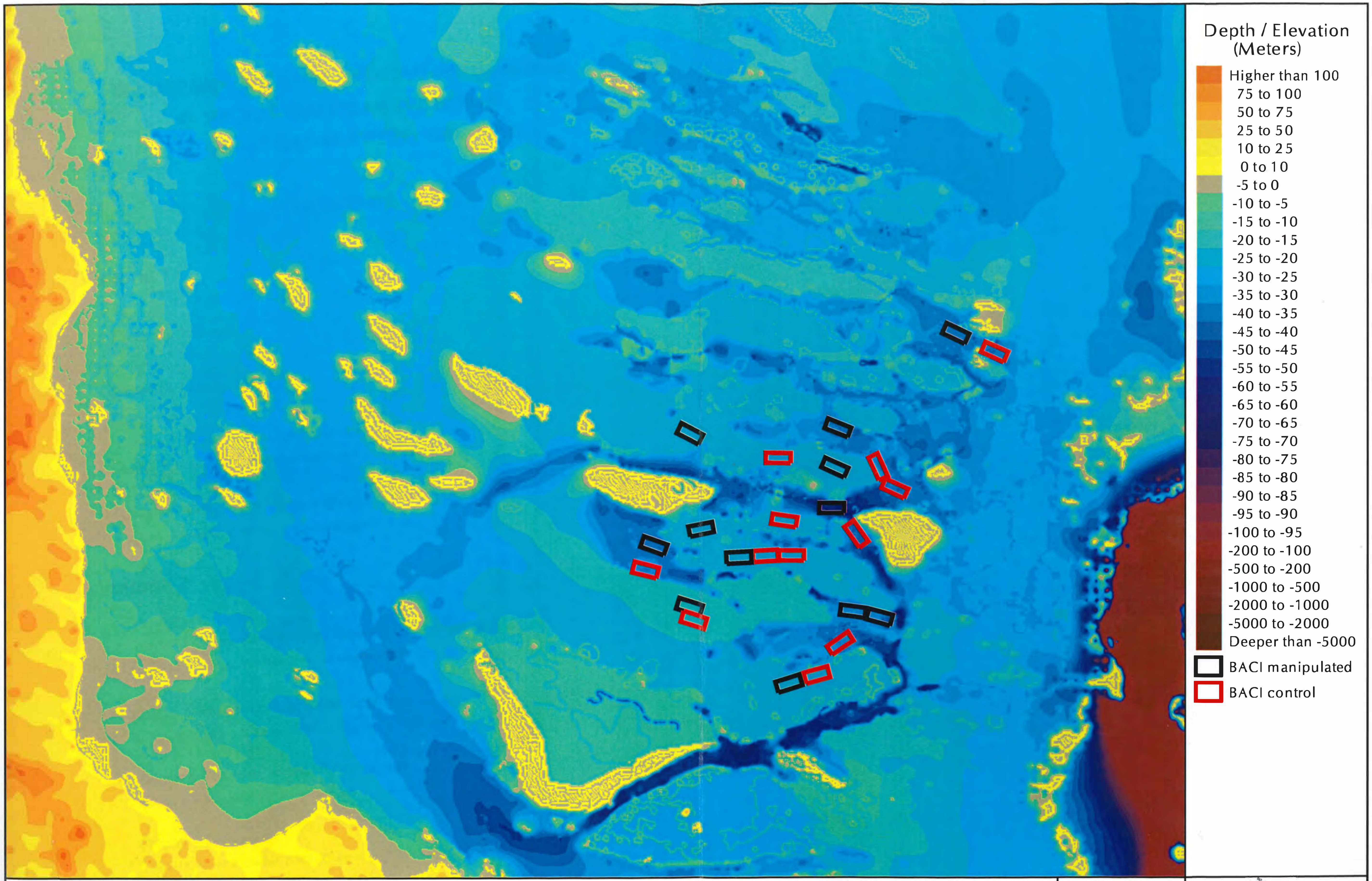


Plate 3. Top – Flower pot coral (*Turbinaria* sp),
Bottom – Gorgonians.



Scale 1:400000

kilometres

5 0 10 20 30 40 50

WARNING: Not for Navigational Use

Sources: CSIRO Marine Research

Bathymetric Range Map
Figure 4.01

Showing the location of the BACI sites in the Far Northern section of the Great Barrier Reef.

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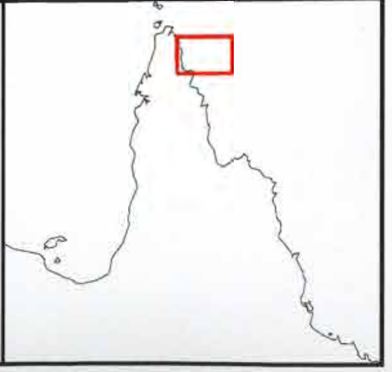

ENVIRONMENTAL EFFECTS OF PRAWN TRAWLING
IN THE FAR NORTHERN SECTION OF
THE GREAT BARRIER REEF: 1991 - 1996

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Authors: C. Burridge, R. Pitcher, T. Wassenberg and N. Gribble

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Authors: I. Poiner, R. Pitcher, B. Hill, C. Burridge, T. Wassenberg, S. Blaber and N. Gribble

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1998

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Masters: Alan Wallace, John Abbey, Alex Ripley, Bruce Hansford
Engineers: Harry Jamieson, Charlie Scott, Graham Helson
Mates: Greg Poultney, Bob Curry, Rudi Franz, Grant Maughan
Crew: Tom Vogler
Cooks: Jo Hayden, Erica Scott, Lyn McKillop

Gwendoline May Crew members:
Masters: Phil Smith, John Abbey, Colin Cant
Mates: Glen Chisholm, Mike Holdsworth, Larry McKinlay
Crew: Mike Smith, Paul Leeson, Julius Florence, Narelle White
Cook: Sally Miller

Sunbird Crew members:
Owner/master: Bert Ziviani

James Kirby Crew members:
Masters: David Duncan, Mark Lennard Crew: Don Battersby

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The Great Barrier Reef Marine Park Authority supplied base maps showing coastline, reefs and islands in the Great Barrier Reef Marine Park.
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David Proh provided information on weather patterns in the study area.

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

SUMMARY

OF THE MAJOR OUTCOMES AND MANAGEMENT IMPLICATIONS AND RECOMMENDATIONS ARISING FROM THE EFFECTS OF TRAWLING STUDY

This report covers a five year study into the effects of trawling on seabed communities in the inter-shoal and inter-reef areas in the Far Northern Section of the Great Barrier Reef. The study arose from a GBRMPA convened scientific Workshop in 1989 to address the effects of fishing in the Great Barrier Reef region. The Workshop recommended that an experimental study of the effects of trawling should be carried out, taking advantage of the area closed to trawling (Marine National Park B) in the Far Northern Section of the Great Barrier Reef Marine Park. CSIRO and QDPI agreed to undertake the study, which was funded by these organisations as well as GBRMPA, FRDC and AFMA. Following the recommendation of the Workshop, the study was sited in an area known as the Green Zone between about 11°15' and 11°45'S that is closed to fishing as well as in the areas immediately to the north and south of the Green Zone. The study had several components:

1. A collation and review of all known biological, oceanographic and fisheries information available on the study area (Chapter 2).
2. A description of the study area. This included a survey of the sediments, epi-benthos (animals living on the seabed), fish and prawns in the region (Chapter 2).
3. Comparisons of the areas that are open to trawling with those that are closed to trawling (Chapter 3).
4. A Before-After-Control-Impact (BACI design) manipulative experiment comparing areas that were subjected to the Impact of a single trawl coverage with untrawled Control areas (Chapter 4).
5. A Repeat trawl experiment in which strips of seabed were trawled up to 13 times (Chapter 5).
6. A description of the composition of prawn trawl bycatch and the fate of discards from prawn trawling and a study of the interactions between seabirds and discards (Chapter 6).
7. The results are summarised here in 10 outcomes categories based on the original objectives of the work. In addition we have summarised a model describing the effects of differential impacts and recovery rates of the seabed fauna (Chapter 7). Finally, implications of the findings of the study for management of the GBR and for management of the East Coast prawn trawl fishery are discussed (Chapter 7).

1. A collation and critical review of all known biological, oceanographic and fisheries information available on the GBRMPA's Far Northern Section Cross Shelf closure (Green Zone) and areas to the north and south.

Methods

Available published and unpublished information was reviewed. Data on trawling was extracted from QDPI and QFMA logbook records together with interviews with fishers and Boating Patrol personnel.

Main findings

1. There was little published data on biological, oceanographic and sediments of the study area. There was some general information on climate and low resolution (30 min grid) data on commercial trawling. (Some fishing records at 6 min grid resolution became available during the course of the study).
2. Trawl fishing recorded in logbooks showed that most effort in the area north and south of the Green Zone took place in the lagoon. The advent of GPS had enabled trawlers to fish the inter-shoal area to a greater extent than previously possible.
3. There has been a high level of illegal trawling in the Green zone and evidence that up to 40 to 50 boats regularly trawl the area. Misreporting of catch has taken place with catches from inside the Green Zone being credited to adjacent open areas.
4. Illegal trawling in the Green Zone appeared to have taken place mainly in the lagoon, in and around the navigation channel and along the northern and southern boundaries.

Implications for management

1. Enforcement of the trawling closure in the Green Zone has been ineffective and enforcement of this and other closures needs to be addressed by management agencies if the objectives of establishing the closures are to be met.
2. Unenforced closures compromise research designed to provide advice to management.

2. A quantitative description of the sediment characteristics, epi-benthic communities, fish communities and prawn populations of the GBRMPA's Far Northern Section Cross Shelf closure and areas to the north and south.

Methods

A total of 137 sites were sampled for sediment analysis and an additional 81 for carbonate analysis. Fauna samples were the same as the set described in Methods of number 4 below.

Main findings

2.1 Sediment characteristics and strata

1. The sediment-size spectrum showed marked changes across the shelf.

    - Inshore sediment samples had a terrigenous origin and had a low percentage of coarse sediment (gravel) and a high percentage of fine sediment (mud). In the Shelbourne Bay region there was a high silica sand content.

    - Offshore sediment samples had a biogenic origin with a low percentage of fine sediment and a high percentage of coarse sediment.

2. Depths in the study area ranged between 13 m inshore and 60 m offshore with some reefs and shoals rising to the surface.

3. The currents in the study area were mainly wind and tidally driven. The wind-driven currents were longshore and in a northerly direction, except in the monsoon season (December–March), when the currents were southerly. Strong tidal currents occurred in the channels between the offshore shoals and reefs but there appeared to be little net flow. This current regime would maintain the longitudinal stratification of the sediment, as there was little cross-shelf transport.

4. The two main zones in the study area – inshore lagoon and offshore inter-shoal, can be divided into five strata on the basis of type of substrate.

    - Stratum A inshore lagoon: muddy sand (30% mud, 65% sand, 5% gravel), medium carbonate (50-80%)

    - Stratum B inshore reefs and lagoon: sandy mud (45% mud, 48% sand, 7% gravel), high carbonate (80-90%)

    - Stratum C inner shoal area: muddy sand (25% mud, 67% sand, 8% gravel), very high carbonate (>90%)

    - Stratum D outer shoal area: sandy (10% mud, 78% sand, 12% gravel), very high carbonate (>90%)

    - Stratum E outer lagoon: sandy (10% mud, 68% sand, 22% gravel), very high carbonate (>90%)

5. The distribution of epibenthos and fish across the shelf appeared to follow five distinct groupings, which correspond, to the five strata identified from the substrate analysis.

2.2 Epi-benthic communities

1. Video transects showed that most of the seabed is relatively bare soft substrate with patches of epibenthic communities made up of a wide diversity of sessile invertebrates including sponges, hard and soft corals and gorgonians with a rich associated fauna of echinoderms, crustaceans and fish. The patchiness of the benthic communities can be visualised as islands of biodiversity in a sea of sand.

2. There was high diversity in the study area: we sampled 763 invertebrate taxa in the dredge including 224 molluscs, 166 crustaceans, 121 echinoderms, 88 cnidarians, 84 sponges, 54 ascidians and 24 bryozoans.

3. We collected 504 species in the inshore strata and 608 in the offshore strata suggesting that both communities are rich in the number of species. There were 335 to 340 species common to both inshore and offshore sites.

4. The epibenthic communities showed strong cross-shelf (east-west) variation. There was a decline in the number of species caught per dredge haul from 49 species per 15 min dredge sample inshore to 20 to 30 offshore but there was an increase in the biomass from 4 kg per haul inshore to 10 kg per haul offshore.

2.3 Fish communities

1. We sampled a total of 340 species of fish in the Green Zone indicating a high diversity of fish.

2. Species area curves indicated that the sampling had probably captured the majority of species. The curves reached an asymptote more rapidly for inshore than for offshore species suggesting more heterogeneity offshore than inshore.

3. Most fish caught in fish and prawn trawls were small – over 85% were less than 30 cm in length.

4. There was a change in the number and composition of species caught from inshore (166 to 180 species) to offshore (193 species). There was also a large overlap in the species composition with 111 to 119 species being captured in both areas.

5. There was a change in total biomass of fish from around 132 kg per 30 min trawl inshore to around 55 kg per 30 min trawl offshore.

2.4 Prawn populations

1. Twenty two species of prawns were found, six of these are commercially important to the prawn trawl fishery although only three, *P. esculentus*, *M. endeavouri* and *P. longistylus,* occurred in commercial quantities.

2. Spatial aggregation was observed at two scales in the distribution of prawn species; a broad onshore to offshore (cross-shelf) trend in species abundance and more localised areas of concentration associated with habitat types and/or aggregation behaviour. Each species tended to aggregate in particular areas that were different between species. Substrate type and rugosity of the seabed were the main features affecting the distribution of prawns. High natural variation was observed in species abundance and biomass, due the uneven "patchy" spatial distribution and to lunar and seasonal periodicity.

3. Two broad groupings of prawn species were apparent:

   - An inshore reef lagoon group, predominantly *P. esculentus* and *M. endeavouri*;

- An offshore shoal-reef group, predominantly *P. longistylus* and a suite of coral prawn species.

4. Overlap in species distributions occurred inshore, probably due to the presence of inshore reefs and islands giving overlapping habitat types.

Implications for management

1. The Green Zone can be divided into five strata on the basis of sediment types. This is different to the central GBR which is usually regarded as having three strata.

2. Extensive areas of soft sediments, muds inshore and sands offshore dominated inter-shoal areas.

3. Most trawling is conducted in soft-bottom areas so sediment type is a good indicator of bottom-types suitable for trawling.

4. Although substrate is a good indicator of benthic communities, it is not sufficient by itself. Other factors such as depth and currents must be taken into account. Further work is needed on these relationships before any rapid assessment technique could be applied in the GBR.

5. No single stratum within the cross-shelf would be representative of the entire cross-shelf community.

6. Inshore and offshore areas were both valuable in terms of biodiversity.

7. Because the density of epibenthos was lower offshore, a larger area would be needed to represent offshore benthic communities in a marine representational system.

8. The inshore region also supported a diverse community. This different community should be taken into account in any planning to establish representative marine protected areas.

9. The high variation coupled with the strong "patchy" nature in the distribution of prawn species will:

    - require careful sampling design in fishery independent surveys of prawn abundance

    - reduce the precision possible in statistical evaluation of management measures such as area closures.

10. The aggregation of prawn species allows "targeting" by prawn trawl skippers that could result in an artificially high catch-per-unit-effort (CPUE) because the aggregations were targeted. This "hyper-stability" reduces the accuracy of monitoring the fishery using simple logbook CPUE records as the index of abundance.

11. P. longistylus (red spot king prawn) occurred in commercial quantities in the offshore shoal-reef region of the cross-shelf transect.

3. List of species of fish caught by prawn and fish trawling and for these species an assessment of the life-history stages and proportion of their populations captured by prawn trawlers derived by comparing the catch of fish and prawn trawls

Methods

Fish catches from fish and prawn trawls from 122 stations were compared; 49 stations in 1992 and 73 in 1993. The fish were identified and either measured or weighed. The results were used for analysis of species and size composition.

Main findings

1. A total of 340 species of fish were captured, 243 in prawn trawls and 236 in fish trawls. A full list of species is supplied in the report.
2. Ninety-five species of fish that were caught in fish trawls were not taken in prawn trawls.
3. Prawn trawls caught smaller species of benthic fish than did the fish trawl. The latter caught more epibenthic and pelagic fish.
4. Over 90% of fish caught in the prawn trawl were less than 30 cm in length.
5. A comparison of the catch from 122 paired fish and prawn trawls showed that although recreational or commercially important fish did occur in inter-shoal areas, extremely few were caught by the prawn trawl. Only eight *Lethrinus laticaudis* were captured in prawn trawls compared to 922 in fish trawls. The fish trawl caught large individuals of *Plectropomus maculatus*, *Lutjanus malabaricus*, *Epinephelus tauvina* but these were not taken in the prawn trawl. Fish trawls caught 11 *Lutjanus sebae* but only one was caught in the prawn trawl.
6. With the single exception of *Diagramma pictum*, the prawn trawl did not catch juveniles of any recreationally or commercially important fish species.
7. The size frequency distributions of fish from fish and prawn trawls were compared for 29 species that were caught in sufficient numbers in both gears for analysis. Six species showed significant differences in sizes with the prawn trawler catching smaller sizes. The differences were large for only two species – *Diagramma pictum* (mean size 10.2 cm in prawn trawls compared to 34.6 cm in fish trawls) and *Scolopsis taeniopterus* (mean size 9.9 cm in prawn trawls compared to 15.4 cm in fish trawls).

Implications for management

1. Prawn trawls mainly capture small species of fish that are associated with the seabed. Many larger species of epibenthic and pelagic fish are not taken in prawn trawls and so prawn trawls are impacting only part of the fish community.
2. Although recreationally and commercially important species of fish occur in the inter-shoal in the Far Northern Section of the GBR, prawn trawls seldom catch juveniles or adults of those species. Thus there is little overlap between recreational or commercial line fisheries and prawn trawl fisheries in this part of the GBR.
3. The results suggest that for species that can be captured by a prawn trawl, with the exception of two species (*Diagramma pictum* and *Scolopsis taeniopterus*) all size/age stages are vulnerable.
4. The extent of impact of prawn trawling on fish populations is probably low given the generally low fishing effort in the Far Northern Section of the Marine Park.

4. Comparison of the benthic communities and fish communities of the area closed to trawling with adjacent areas open to trawling

Methods

A random sampling strategy was used for collecting samples of the fauna at sites within the Green Zone and in the areas to the north and south. In 1992 a total of 66 sites were sampled by fish trawl, 49 by prawn trawl and 72 by benthic dredge. In 1993 a further 86 sites were sampled by fish trawl, 77 by prawn trawl and 85 by dredge. Four data sets were analysed from these collections: prawns from the prawn trawl; bycatch (fish and invertebrates) based on prawn trawl catches; fish species based on fish trawl fish catches and benthic invertebrates from the dredge.

Main findings

1. The mean estimate of the power of the open versus closed comparison was the capability to detect a difference in fauna by 41% between the zones.
2. We found no significant differences between the area closed to fishing (the Green Zone) and the adjacent open areas that could be attributed unambiguously to trawling. Many of the differences we found between the Green Zone and adjacent areas were probably due to environmental factors other than prawn trawling
3. The lack of an observed difference between the closed and adjacent open areas that could be attributed to prawn trawling was probably due to the existence and interaction of a number of the following features:
    - There was a very high level of natural variation in the population density of marine animals
    - The Green Zone was in fact partially trawled especially in the inshore strata. In addition a large part of the open area was not trawled.

- The GBRMPA 6 min grid analysis showed that the distribution of trawl effort in the open areas was highly variable both at the large scale (30 n.mile grids) and the medium scale (6 n.mile grids). QFMA VMS monitoring data showed that effort was also variable and not evenly spread over the available area at the small scale (1 n.mile grids).

- Most areas are subject to relatively light trawling each year. The GBRMPA analysis showed that only seven of 200 grid squares (6 x 6 n.miles) in the vicinity of the Green Zone were trawled sufficiently to have a coverage amounting to more than twice a year.

4. It was not possible to stratify our survey to take account of this variation in trawl intensity because information on trawl effort in the area was not available at a sufficiently high resolution at the time of the study and is still not available.

Implications for management

1. Within this zone there was a strong gradient in the east-west direction in terms of the physical environment (sediment and topography) and biological communities. This vindicates the choice of a cross-shelf transect to represent these different environments.

2. There were also smaller but distinct north-south differences in the physical environment and biological community in the 1 degree of latitude centred on the Green Zone and including areas open to trawling. The fact that these differences were detectable even in an area this small relative to the whole GBRMP suggests that there may be even larger differences between the Green Zone and other areas such as the Central and Southern Sections. Therefore the Green Zone may not be a suitable representation of the entire GBRMP.

3. If GBRMPA wishes to establish unfished cross shelf areas in the GBRMP, several other ‘Green Zones’ may be needed in order to capture differences due to latitudinal gradients in species distribution in the whole Great Barrier Reef Marine Park.

4. We concluded from this part of the study that it will never be optimal to attempt to measure the impact of trawling solely by comparing areas open and closed to fishing, without additional supporting information. This is not simply because sampling a single ‘Green Zones’ is technically pseudo-replication. Even if there were several ‘Green Zones’, it is unlikely they would be true replicates or could be assumed to represent, in entirety, appropriate control sites within each ‘region’. Even with several ‘Green Zones’, open versus closed comparisons are not an optimal method for assessing the impact of trawling. This is because of the uneven patchy spatial distribution of trawl effort in open areas, as well as significant open areas that are untrawled. Further, the overall average level of trawling effort is low, in relation to the level estimated to cause statistically detectable impact.

5. We have concluded that even fully replicated two-state comparisons (open vs closed) are not an optimal method. We suggest the most appropriate way to estimate what the effects of trawling have been in the bulk of the GBR lagoon will be to precisely identify and sample, in several regions of the GBR, many replicate

small-scale sites on a gradient of the full-range of actual trawl intensities. This suggested multi-state approach would have more interpretive power. Any real trawl effects should show a trend with trawl intensity, and will be less sensitive to spurious confounding effects.

6. A controlled depletion-experiment on soft-sediments should be conducted to provide pilot information that is necessary for designing the larger-scale sampling. This would also enable estimation to be mad of the impact rates for soft-sediment fauna. A depletion-experiment would also complement the larger-scale sampling and provide corroborative evidence on the effects of trawling on soft-sediment fauna. This approach will require grid-scale and fine-scale information on trawl effort distribution, and ecological information on the distribution of habitat types.

7. The introduction of VMS will greatly assist in understanding and quantifying the extent of trawl effort but the usefulness of the data will depend on the number of times a day each vessel is checked (polling rate). A high polling rate will be necessary at least in some areas to accumulate information on the intensity of trawling over discrete parts of the seabed.

5. Assessment of the impact of prawn trawls on benthic communities and fish communities and the response of these communities to the cessation of trawling. This objective to be achieved by an experimental manipulation of trawl effort.

Methods

1. A BACI (Before-After-Control-Impact) experiment was set up in the Green Zone in areas that were suitable for trawling but were apparently untrawled. Twenty-four plots 2.8 x 1.22 km were identified, 12 of these were in shallow water and 12 in deep water. Each plot was sampled by using a replicated video sled, a benthic dredge, a prawn trawl and a fish trawl to give Before information. Six plots at each depth were trawled all over once (Impact) and the remainder were used as Controls. All plots were then resurveyed to give After Control and Impact information. A single-coverage BACI experiment was set up because of the precedent on the North West Shelf (also a tropical, continental shelf environment), where a single trawl had been found to remove 90% of sponges for which the fate was known from video taken during trawling. Based on research data, the average catch rate of sponges on the North West Shelf fell from around 500 kg/hour to only a few kilograms/hour (Sainsbury, 1987). The large scale of the BACI experiment was also determined by the need to cover as large an area as possible to test larger scale ecological effects on moderately mobile species.

2. A Repeat Trawl depletion experiment was carried out on a track in each of 6 plots. In each case, 13 trawl tows were made along the same track. Records were kept of the catch from each tow and in addition non-destructive video sampling was made during the course of the depletion.

Main findings

1. Despite the removal of around 40 t of benthos during the impact phase of the BACI, and contrary to the prior expectations of GBRMPA, the scientists involved in the design of the project, prior evidence and community perceptions, the single trawl coverage produced no detectable impact. The BACI experiment was expected to have an 80% statistical power to detect a reduction down to less than 10%-30% in biomass, and for most taxonomic classes the experiment was more powerful than the *a priori* estimate. We conclude that the impact of a single trawl coverage in the FNS of the GBR must be smaller than 90%.

2. The apparent density of benthic invertebrates sampled by prawn trawls was much smaller than by the benthic dredge suggesting an average removal rate much closer to 10% than 90-100% per trawl.

3. The prawn trawl is relatively good at catching crustaceans (40% efficiency relative to dredge) and relatively poor (0-10% efficiency relative to dredge) at catching most other benthic organisms – whether sessile or mobile. Data from prawn trawl catches do not show which organisms are completely unaffected by trawling, or which organisms are fatally damaged but not removed.

4. Preliminary sampling was carried out to monitor recovery from the BACI experiment, starting from 12 months after the impact. However, no impact was detected from the sampling 6 months after the impact. It was not possible to estimate recovery rates from this experiment. The first of the recovery monitoring samples was included with the post-impact sample as a second assessment of the impact. No clear trend was detected.

5. The Repeat-trawl experiment also suggested that each trawl removed 10-15% of that part of the sessile benthos community, the mobile benthos community and the fish community that are vulnerable to trawling.

6. The Repeat-trawl experiment, with a high degree of control over trawl navigation and a detailed assessment of the entire catch, produced data with high variance even for sessile invertebrates that cannot move in response to the disturbance.

7. The Repeat trawling experiment caused a more substantial impact than the BACI experiment, though limited to a much smaller area.

8. Prawn trawlers do not follow a 'wheat field harvesting' spatial distribution in which the whole trawl ground is trawled at the same intensity. VMS data from vessels operating in the prawn fishery shows that prawn trawlers tend to 'work' an area for a number of days, to trawl many times along paths they have previously found productive, and to avoid those they found unproductive or hazardous.

9. A new GBR Recovery Monitoring project that focuses on the sessile megabenthos has been started to monitor recovery from the Repeat-trawl impact experiment.

Implications for management

1. In the BACI experiment, the impact of a single prawn trawl coverage was not detectable. Comparison of catches by different gears indicated that the impact might have been around 10%, not around 90%.

2. The apparently lower level impact of a trawl in the northern GBR compared to the North West Shelf is probably due to the latter study having been targeted at that portion of the seabed benthos that is most vulnerable to trawling – namely large sponges. The GBR study by contrast considered all sponges including the many small encrusting species that are less likely to be impacted and it also considered the full suite of epibenthic species. It appears safe to conclude that a single prawn trawl does not have the very large across-the-board impact that had been expected on the basis of the NW Shelf study.

3. The composition and quantities of benthos catch in prawn trawls do not give a representative picture of the benthic invertebrate community because the gear is selective.

4. BACI-style experiments of the effects of prawn trawling in the GBR inter-shoal would need to apply a greater impact than given by single trawl coverage to produce a statistically significant result. This will require a considerable trawl effort: either to create a much larger impact (around 10 to 15 times as much coverage) or to sample much more intensively (as much as 100 times more). Given the high cost of ship time, this would be an extremely expensive experiment.

5. Repeat-trawl-style experiments in the GBR inter-shoal areas can provide very useful information on trawl depletion rates. The results of each experiment are applicable only to a small subset of the marine community because of the variability of the seabed ecosystem and so they would need to be duplicated in a range of appropriate habitats.

6. The data set from the repeat-trawl experiment is a prototype for the type of information that could be collected once VMS is operational. However even VMS data will not provide the fine level position information used in the repeat trawl experiment. Repeat-trawl data provides a good basis for developing a more complex mathematical/statistical model that addresses some of the issues that have been identified in this experiment but have not yet been built into a model.

7. The current project was not able to give any estimate of recovery rates. However it is essential to measure the rate at which the community recovers in order to determine the real impact of trawling which is an interaction between the dynamics of depletion and recovery.

6. A quantitative description of penaeid prawn species composition and abundance in both undisturbed areas and those with a history of trawling activity

Methods

Prawn trawl samples were collected from 51 sites from within the Green Zone and to the areas to the north and south of the closure in May to June 1992. An additional 79 sites were sampled in March to May 1993. Prawns were separated from the catch, identified and measured.

Main findings

1. There were large year to year variations in prawn populations.
2. The brown tiger prawn *Penaeus esculentus* and the endeavour prawn *Metapenaeus endeavouri* had clear relationships with substrate type. They were much more abundant in muddy sediments low in calcium carbonate. The red spot king prawn Penaeus longistylus, did not show a clear relationship with substrate but it did show a positive relationship with depth.
3. Catches of *Penaeus esculentus* and *Metapenaeus endeavouri* were influenced by the lunar cycle.
4. The abundance of prawn species, particularly those exploited commercially, was significantly higher in trawled areas than in areas closed to trawling.
5. Conversely the reef-associated “coral prawns” had a significantly lower abundance and diversity in trawled areas.

Implications for management

1. Because different species occupy different areas, the effectiveness of area closures to protect penaeid stocks depends on the distribution of individual species.
2. Optimum ecological sustainability and economic return may be achieved by careful control of trawl effort and by selective use of area closures.

7. A quantitative description of the composition of bycatch produced by prawn trawls in the cross-shelf transect and to the north and south. This was to be based on research catches in the region.

Methods

Bycatch samples were collected from 79 research prawn trawls in the inshore region and 43 in the inter-shoal region both within the Green Zone and the areas to the north and south of the closure. These samples were analysed for species composition.

Main findings

1. The mean catch rate of bycatch by a single prawn trawl net was 37 kg per hr in the lagoon and 55 kg per hr offshore. Most of the difference was due to the offshore catch rate of invertebrates being about double that of the inshore catch rate.

2. A total of 245 species of fish (9 elasmobranchs and 236 teleosts) were caught in these trawls. A full list is given in the report. Catch rates and mean sizes are also given for each species.

3. Over 100 species or taxa of invertebrates were collected in these prawn trawls. The final number of species is uncertain because specialists have not completed many identifications. A listing of the invertebrates together with the catch rates and mean sizes for each species or taxon is provided in the report.

4. Fish and crustaceans dominated the bycatch. Fish made up around 72% of discards by weight from lagoon trawls but only 60% of inter-shoal discards. Crustaceans accounted for 7% of the bycatch weight from the lagoon and 13% from the inter-shoal area.

5. Some groups were dominated by a few species: The two most abundant species of fish made up 22% of the fish catch by weight in the lagoon and 25% in the inter-shoal area. Two species of crabs made up 77% of the lagoon and 88% of the inter-shoal crustaceans by number. One species of heart urchin accounted for 48% of the echinoderms caught in the lagoon.

Implications for management

1. The bycatch composition of trawling in the Far Northern Section displayed a high diversity similar to that found in neighbouring tropical prawn fisheries.

2. Most of the bycatch taken in prawn trawling in the Far Northern Section of the Marine Park has little or no commercial value and will be discarded.

3. The composition of discards from the commercial fishery will vary depending on whether trawling is inshore or offshore and so depends on the target species of the prawn fishery.

4. Introduction of BRDs using designs currently available would lead to a reduction of about 20% in the amount of bycatch taken by prawn trawlers. This would reduce the impact of trawling on small demersal animals and especially on fish that have a particularly low survival rate from trawling. It would however not address the question of sustainability of the species captured. This aspect is the subject of a current research project (See Number 13 below).

8. A list of species of trawled animals (vertebrates and invertebrates other than prawns) returned to the sea alive and dead, and quantification of the fate of the dead material

Methods

Composition of discards was obtained from the catches reported in Number 7 above. Buoyancy was tested on discards collected from ten commercial duration (165 min) trawls carried out in the inshore region and a further ten carried out in the inter-shoal region. Observations were made on surface scavenging of floating discards at night and during the day and on seabed scavenging at night. The size composition of fish eaten by seabirds was estimated by analysis of fish otoliths collected from seabird pellets.

Main findings

1. Fish were the major component of discards; previous work showed that over 90% of fish are dead when discarded from prawn trawls. The second most important group of discards by weight was the crustaceans; crabs dominated these. Survival experiments on crabs showed over 90% were alive four days after being trawled.

2. Between 34 and 40% of discards by number and weight from the lagoon floated compared to only around 10% of discards from the inter-shoal area. Fish made up nearly all of the floating discards.

3. The majority of fish were small (<20 cm total length) with a modal length of around 12 cm

4. There was little scavenging of floating discards at night but during the day seabirds (mainly Crested Terns and Frigatebirds), dolphins and sharks were seen to take discards at the surface.

5. Because seabirds only take floating fish that are mostly less than 12 cm in length and because most fish sink, it was estimated that seabirds account for only a minor part of the discards

6. Teleost fish and sharks were the most important scavengers of discards on the seabed

Implications for management

1. About 80% of the discards are dead when dumped because very few fish, which are the dominant group, survive trawling. Robust forms such as crabs and bivalves have high survival rate but made up a minor proportion of the discards.

2. Seabirds take only a minor proportion (<10%) of discards from inter-shoal trawling and so most discards end up on the seabed.

3. Because discards are dispersed over the seabed, and most seabed scavengers forage over restricted areas, discards probably do not cause measurable seabed impacts

4. The following conceptual model divides the scavengers groups into three groups with the possibility of their populations being affected:

Scavenger group	**Composition of group**	**Distance of daily scavenging activity**	**Impact on populations relative to trawling intensity**
Group A	Seabird species that take discards	Tens of kilometres	Possible even in lightly fished areas because of ability to forage widely
Group B	Dolphins and sharks	Kilometres	Possible in areas of regular trawling because they can concentrate in these areas
Group C	Small fish and invertebrates on seabed	Tens of metres	Likely only in areas of regular trawling

9. Quantitative estimates of the importance of trawl discards in the diets of seabirds, the degree of dependence on such discards and the effects of discards on seabird populations

Methods

Diet samples were collected from 12 species of seabird in the Far Northern Section of the GBR. Fish prey items were identified from otoliths by means of a CSIRO reference collection. Data on abundance and breeding seasons of the seabirds were obtained by visiting nesting sites as part of a longer-term study of seabird populations.

Main findings

1. Trawl discards were important in the diets of only three species of seabird (Crested Tern, Brown Booby and Lesser Frigatebird). They were of minor importance to another four species and were not eaten by another seven species that were investigated.

2. No seabird species was entirely dependent on discards, but the diet of Crested Terns consisted largely of discards during the trawling season.

3. No effects of discards were detected on any seabird populations with the exception of those of the Crested Tern. Populations of this species have increased by two orders of magnitude in the far northern Great Barrier Reef since trawling began.

Implications for management

1. An increase in the amount of trawling may result in a greater intake of discards by at least three species of seabird with possible increases in population sizes. This outcome would be likely if the present populations are food limited.

2. Cessation or significant reduction of trawling or the introduction of BRDs in the Far Northern Section of the BGR will lead to a decrease in the amount of discards. This may lead to a reduction in the populations of Crested Terns in the area. This would probably be through a reduction in recruitment of young birds to the population rather than through mortality of adults.

10. Differential vulnerability to trawls and differences in recovery rate as determining factors for epibenthos abundance and composition in trawled areas

Methods

The overall effects of trawling are dependent on the distribution and intensity of effort, which is known to be patchy. We extended the key experimental results to estimate the depletion rate of attached fauna subject to a range of trawl intensities observed in the fishery; the total annual removal of fauna from the GBRMP; and the possible status of populations of attached fauna after 20 years of trawling. In attempting to estimate population status, it was necessary to add a simple model for possible recovery dynamics of fauna. This extension of the results to trawled areas of the GBR Marine Park was speculative, and several assumptions were necessary in order to proceed with the analysis.

Main findings

1. Trawl effort is highly aggregated among 6 minute grids, with about 20% of the effort concentrated into <5% of trawled grounds (intensive) — at the other extreme, about 20% of the effort is spread over about 60% of the trawled grounds (extensive).

2. Rigorous information on the spatial intensity of trawling within 6 min grids is only just becoming available, but that available from research in the NPF and from VMS suggests that trawling is also highly aggregated at very fine scales.

3. The removal rates (resilience) of most seabed fauna was between 5–20% per trawl, but ranged up to 0–40% per trawl. The amount of fauna removed each year is related to the resilience of the fauna and the intensity of trawling. In lightly trawled grids, the annual removal may have been only a few percent, but in the most intensively trawled grids, more than 80% of the least resilient fauna may be removed each year.

4. The average total annual removal of fauna from all trawled grids in the GBRMP may have been about 10% per year, but would be different for different fauna. About 4% of high resilience fauna may be removed, ~8% of medium resilience fauna, and ~15% of low resilience fauna.

5. If fauna have no capacity for recovery, then eventually, all trawled seabeds will become completely denuded of fauna. With capacity for recovery, then all faunal vulnerability types have the potential for sustaining a population level in balance with the amount removed by trawling — up to a limit that is highly dependent on the intensity of trawling. The most vulnerable fauna may become 'extinct' in 5–10% of grids that are trawled with >2,000–3,000 hrs of effort; more fauna will become 'extinct' in grids with higher effort. Because of differential vulnerability, community composition will be substantially altered in most grids.

6. The possible overall status of attached fauna after 20 years of trawling in all trawled grids in the GBRMP may be a depletion of ~20%, but would be different for fauna with different vulnerability's. Fauna with low vulnerability may be depleted by about 3%; medium vulnerability fauna may be depleted by about 20%; and highly vulnerable populations may be depleted by about 55% overall.

Implications for management

1. Large areas of the GBR are subject to trawling. In 1996, effort was recorded in 1300 6 min grids — an area equivalent to ~160,000 km^2

2. Trawling is aggregated within grids, consequently less area is actually trawled than is indicated by summing up 6 min grids.

3. Aggregated trawling removes less benthos in high effort grids, than if effort was distributed randomly or uniformly.

4. Each year, trawling removes between 4–15% of seabed fauna from all trawled grids in the GBRMP.

5. Though 50-70% of trawled grids have been trawled only lightly (<700–1000 hrs) each year, over the last 20 years the cumulative effect of this has been that:

    - vulnerable types of fauna (ie. those easily removed and/or slow to recover) have been severely depleted, thus causing

    - substantial changes in the composition of the faunal community, and

    - the overall faunal biomass may have been reduced by ~20%, but it would be dominated by "weedy" species.

6. Caution is needed in accepting these conclusions because it was necessary to make several assumptions to conduct the analysis. The actual situation could be better or worse than the conclusions presented above.

7. The assumptions can be minimised with better information on: the distribution of effort among grids; the fine scale distribution of effort within grids; the effects of trawling on soft-sediment fauna; the distribution of fauna; and the recovery rates of fauna.

8. Trawling is potentially ecologically sustainable if there is appropriate management of the impacts.
    - The type of modelling summarised here can be developed to assist by indicating the potential consequences of a range of scenario for management interventions.
    - This approach would also applicable to other issues affecting trawl industry and its management; such as impacts on bycatch populations.

11. Utility of the results and conclusions for the management of the Great Barrier Reef

Main findings

1. The inter-shoal areas of the northern GBR are characterised by a high diversity of fish (we collected 340 species) and invertebrates (we collected 687 species or taxa). The inter-shoal area also has a diverse range of habitats ranging from relatively bare open sandy or muddy flats to highly diverse patches of reef.

2. Contrary to the commonly accepted three strata model derived from the central GBR, we established that the northern GBR in the vicinity of the Green Zone has five distinct zones. These can be broadly characterised on the basis of sediment type, invertebrate and fish populations although there are not five discrete community types.

3. There has been an unacceptably high level of illegal trawling within the lagoon of the Green Zone; this has compromised the difference between the areas closed and open to fishing.

4. We did not find any significant differences between the area closed to fishing and the adjacent open areas that could be unambiguously attributed to trawling. There are at least four possible explanations for this:

5. The level of illegal trawling in the closed area has been sufficiently high to blur any difference that may have arisen since the zone was closed. On the other hand, much of the open area is not trawled.

6. The level of natural variability was so high that it is difficult to detect a statistically significant difference, due to trawling, between the areas. The open versus closed experiment could have detected whether the biomass in one zone was 41% of the other. This would be equivalent to a medium sized effect.

7. The difference between the area to the south of the Green Zone and the area to the north was greater than between the Green Zone and these areas. This change in faunal composition also contributed to any differences that could be attributed to fishing.

8. A single pass of a prawn trawl has less impact than a reduction to 41% so the impact on the seabed cannot be detected especially if the level of effort in the open areas is low and there is trawling in the closed area.

9. The BACI experiment showed that the impact of a single trawl in the northern GBR was not as severe as had been expected on the basis of observations on the North West Shelf of Western Australia. This difference is due to NW Shelf study targeting that part of the epibenthos that is most vulnerable to trawling, namely large sponges. The GBR study included all sponges including the many encrusting types as well as measuring the impacts on the full range of invertebrate groups as well as fish. The result is that the GBR experiment is a far more intrusive study with information that has important implications for management.

10. The Repeat-trawling experiment indicated that a single trawl removes 5 and 25% of the benthos depending on the species. Repeated trawling has a cumulative effect such that around seven trawls over the same ground will remove about half the benthos. This impact is far less than reported in the literature for beam trawls in the North Sea or scallop dredges and suggests that prawn trawls cause less damage than these heavier gears that tend to disturb the seabed to a greater extent. However, the differential impact on various species together with differences in recovery rates, will lead to a change in species composition in areas that are trawled frequently. It is unlikely that any trawled areas now have the original unfished faunal composition.

11. Assuming that commercial trawlers collect the same quantities of bycatch as was taken in research trawls, average discards per trawler would be around 750 –1100 kg of discards each night. These figures must be treated with caution since they can be expected to vary seasonally and with the area fished. The figures show a large amount of discards is produced. The main scavengers of discards in inter-shoal areas are sharks and fish. Seabirds take only a minor proportion because most discards sink and of the fish that float, only half fall within the size range eaten by seabirds

12. The only species of seabird apparently affected by feeding on discards is the Crested Tern. Populations of this species have increased by two orders of magnitude over the time of the trawl fishery. This increase may have been the result of greater availability of discards for young birds.

Implications for Management

1. GBRMPA and the scientific community need to pay more attention to inter-shoal and inter-reef areas. Until the present study, the main focus of research and management has been on the reefs of the GBR and yet these make up only 5% of the GBR Marine Park. Nearly all of the research funding and effort on the GBR has therefore been applied to a minor part of the whole system.

2. There is little point in closing areas to fishing if the closures are not enforced. GBRMPA needs to work more closely with management and enforcement agencies to ensure that closures such as the Far Northern Green Zone are effectively policed. The introduction of VMS to the Queensland trawl fleet should substantially improve enforcement of closures for trawling.

3. It is difficult to assess the impact due to trawling by comparing areas open to fishing with large closed areas if there is a high habitat and fauna diversity. This problem is exacerbated if the closed area is trawled and fishing effort in the open areas is low. This difficulty in using closed areas to estimate the impact of trawling would apply even if there were multiple closed areas in the GBR.

4. A single trawl appears to have less impact on the inter-shoal community than had been expected on the basis of studies on the North West Shelf. This latter study however concentrated on the most vulnerable components of the benthic fauna namely large sponges and we consider that the results of the GBR Effects of Trawling study have produced results, which are more realistic and applicable since they include a wide range of epibenthic organisms.

5. While a single trawl has little detectable impact on the benthic communities, repeated trawling will gradually remove the animals and plants that are attached to the bottom as well as reduce the fauna associated with them. Though over the last 20 years 50-70% of trawled grids have been trawled only lightly (<700–1000 hrs) each year, the cumulative effect of this has been that: vulnerable types of fauna (ie. those easily removed and/or slow to recover) have been severely depleted. This has probably caused substantial changes in the composition of the faunal community. The overall faunal biomass may have been reduced by ~20%, but it would be dominated by "weedy" species.

6. Trawling is patchily distributed in the GBR and is related to the density of commercial prawns. Trawl effort is highly aggregated among 6 minute grids, with about 20% of the effort concentrated into <5% of trawled grounds (intensive) — at the other extreme, about 20% of the effort is spread over about 60% of the trawled grounds (extensive). There is an urgent need to study the rate at which communities recover from a trawl impact. If the rate is slow, then even low levels of effort repeated annually may eventually cause a serious impact. This is fundamental knowledge that is essential for sustainable management of the GBR inter-shoal areas.

7. Discards are probably not causing any environmental impact on bird populations other than crested terns. Because seabirds can forage over wide distances, local closures are unlikely to impact on them.

12. Utility of the results and conclusions for the management of tropical prawn fisheries

The Queensland Fisheries Management Authority has produced a draft Proposed Management Arrangement for the Queensland Trawl Fishery East Coast and Moreton Bay for the period 1998-2005 (QFMA 1998). The results of the GBR Effects of Trawling Study has important implications for the management of prawn trawl fisheries and these have been used as the basis for comment on the Plan as set out in detail in Chapter 7 and summarised below.

1. Effort Control and Reduction

The Plan proposes to cap the total effort at a level no higher than that applied in 1996. Capping and eventually reducing trawling effort will reduce the extent of trawl impact on the seabed. It is possible that the reduction in effort may be greater on the marginal grounds and so will not be evenly spread. Thus we expect that heavily fished areas will continue to be targeted.

2. Closures

The Plan notes that one of the uses for closures is to minimise disturbance of selected marine environments and habitats for general conservation requirements. Despite this preamble, none of the management interventions address conservation and none of the proposed strategies are aimed at improving habitat management.

If closures are put into place for environmental purposes, we recommend that they should target structured, high value habitats. The matters of vulnerability, representativeness and adequacy also need to be addressed. The rate of recovery of habitats from trawling would need to be taken into account if temporal closures were used to benefit habitat.

3. Sustainability indicators

None of the indicators proposed in the Plan are designed to ensure sustainability of the environment, they all deal solely with stocks. We recommend that sustainability indicators should also be developed for non-target habitat and indicator species and the information provided in this Report would be helpful in this.

4. Fishing apparatus, gear restrictions and current regulations

The Plan proposes to reduce the total maximum effort in the fishery to sustainable levels. This is welcomed since any reduction will be helpful to seabed habitats. However, the sustainable levels referred to are for prawn stocks, not the environment, seabed habitat or bycatch. We recommend that the sustainability of the seabed habitat also be taken into account.

We also recommend that management should specify the maximum size of ground gear allowed. This offers a mechanism for reducing or even preventing trawling over structured habitat. If operators cannot use heavier gear they will probably avoid rough seabed to reduce gear damage or loss.

5. Species taken by trawling

The Plan proposes to ensure that species taken by trawling are ecologically sustainable. It also seeks to minimise all impacts of trawling on non-target species. These objectives are welcomed. The main management intervention to achieve the objectives is to introduce Bycatch Reduction Devices (BRDs) into the fishery. We welcome the introduction of BRDs, as this will reduce the impact of trawls on many seabed animals. BRDs will however not lessen the impact of trawls on sessile animals such as sponges. Strategies for addressing sessile animals need to be incorporated into the Plan with indicators or performance measures for these animals being decreasing amounts of bycatch and benthos taken.

6. Endangered or threatened species

Although no seabed species have been listed as threatened or endangered, the introduction of TEDs will reduce the catch of large animals such as rays. It is possible that some of the species taken by trawling may be threatened by trawling. More information on this aspect of bycatch and trawl impacts is needed for the Queensland East coast on the lines of the research presently underway in the Northern Prawn Fishery to establish whether such species exist and what management interventions are needed.

7. Enforcement, compliance and education

A major difficulty with the study of the Effects of Trawling has been that there has been an unknown amount of trawling within the area closed to fishing. We believe that lack of compliance is a common problem with regard to spatial closures and so we welcome the introduction of VMS to the East Coast trawl fleet. This offers the opportunity to improve enforcement of closures and make these a more effective management measure for protection of habitat.

There is presently a large gap in our knowledge of the spatial pattern of trawling, VMS also offers an opportunity to close this gap which will increase understanding of likely impacts and how to minimise them. The amount of information derived from the available funds should be optimised. This could be done by increasing the frequency of polling for areas of low trawl intensity (which would otherwise have little coverage) and reducing polling frequency for areas of high trawl intensity (which would otherwise yield a large amount of duplicate information).

13. Future research into the effects of fishing

The project has led to new research projects addressing a range of problems:

Recovery Monitoring. This is being carried out on the tracks used in the Repeat Trawl depletion experiment in which between 70 and 95% of the initial biomass of attached seabed fauna was removed. The objectives of the project are to document the recovery of seabed fauna after the depletion experiment by assessing the vulnerable species or taxa; the physical structure; and community complexity and measuring their recovery 1, 2 and 4 years after impact. Non-destructive video sampling techniques are being used. Data is analysed for population density, nearest-neighbour distance, height, width, area, percentage missing, and percentage dead of organisms.

Bycatch sustainability. CSIRO with financial assistance from FRDC is carrying out a study of ways to assess bycatch sustainability in tropical prawn trawl fisheries. The distribution of species on and off trawl grounds is being determined together with factors that may make the species especially vulnerable to trawling. For example if the entire population is found only on trawl grounds, or if a critical life history stage is found only on trawl grounds.

Dynamics of large sessile seabed fauna. This study by CSIRO with support from FRDC is measuring the recruitment, growth, mortality and reproduction of structurally dominant large seabed organisms (sponges, gorgonians, alcyonarians and corals).

Methods for monitoring bycatch. The introduction of a range of techniques for reducing bycatch requires an accurate method for monitoring the quantity and composition of bycatch. CSIRO with support from FRDC is presently comparing three different systems for monitoring bycatch of prawn trawlers in the Northern Prawn Fishery.

New projects that are under development include:

Impacts of trawling on soft sediment communities. The GBR study was focused on seabeds having a three dimensional structure. It did not deal with the impacts of trawling on soft sediment fauna and should not be extrapolated to soft sediments. Most trawling in Queensland is over soft bottom sediments and so a new project is proposed that would specifically target these communities.

Mapping of seabed habitats. The main aim of this project is to extend the results of the CSIRO/QDPI “Effects of trawling” study to ensure sufficient representative latitudinal transects of the GBR have been documented to adequately describe the biodiversity and ecosystems of the soft bottom lagoon and inter-reef. Three broad-scale surveys are planned, one each in the northern, central and southern GBR. Each broad-scale survey would be from the near-shore to the outer barrier reef and would encompass 10,000 - 20,000 km^2. Samples will be collected at up to 200 sites in each transect by trawl, benthic dredge, sediment grab, remote video camera and acoustic remote sensing. The distribution and abundance of seabed habitats and biodiversity of associated flora and fauna will be recorded together with environmental factors most likely to influence seabed habitat and species distribution and abundance.

CHAPTER 1

INTRODUCTION

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CONTENTS

1 INTRODUCTION

1.1 The Great Barrier Reef Marine Park Authority (GBRMPA)

Ratification of the Great Barrier Reef Marine Park Act 1975 was the first step in the progressive creation of the Great Barrier Reef Marine Park (GBRMP), which now covers an area of about 350,000 km2 along more than 2,000 km of Queensland's coastline. The principal purpose of this park was to protect the Great Barrier Reef (GBR). To facilitate this objective, the Act established the Great Barrier Reef Marine Park Authority (GBRMPA) with statutory responsibility to manage the Marine Park with the goal of providing protection, wise use, understanding and enjoyment of the resources of the GBR in perpetuity. This responsibility applies to the whole of the Great Barrier Reef Marine Park, including both reef and inter–reef areas. In managing the GBRMP, the Act requires the following to be taken into account:

1. the conservation of the GBR;
2. the regulation of the use of the Marine Park so as to protect the GBR while allowing reasonable use of the GBR Region;
3. the regulation of activities that exploit the resources of the GBR Region so as to minimise the effect of these activities on the GBR;
4. the reservation of some areas of the GBR for the appreciation and enjoyment of the public;
5. the preservation of some parts of the GBR in its natural state, undisturbed by humans except for the purposes of scientific research.

1.2 Trawling as an environmental impact

Although trawling is one of the most important method of fishing worldwide, its continuation and sustainability is being questioned because of its possible environmental impacts (Jones, 1992). In the most heavily trawled areas such as parts of the North and Baltic Seas, the tracks of otter trawl boards alone cross the entire seabed each year (Krost et al., 1990). Despite this intensity of fishing, apparently sustainable trawling has continued for decades and even centuries on some northern hemisphere grounds. In other areas, however, there have been declines that have been linked to the impact of trawling (Bradstock and Gordon 1983). Trawling has several effects apart from reducing the numbers of the target species. Some forms of trawling take large quantities of bycatch which is discarded leading to a range of indirect effects (see review by Dayton et al, 1995). Trawling may also resuspend sediments and raise turbidities (Churchill, 1989). A key impact of trawling is that it can significantly reduce three dimensional structure. Collie et al. (1996) point out that habitats with three-dimensional structure tend to be more sensitive to fishing disturbance than communities with mobile sandy sediments and little three-dimensional structure. Loss of this structure changes the habitat, leading to reductions in populations of animals that are dependent on it for a range of biotic reasons including shelter, food or spawning area. Thus in addition to generally managing the effects of trawling on the seabed, areas supporting large epibenthos need special attention to avoid serious and unsustainable impacts.

1.3 The East Coast Prawn Trawl Fishery

In 1995, the total prawn catch in the Queensland East Coast Prawn Trawl Fishery was about 6 500 t of prawns and 1 200 t of scallops from about 70 000 days fishing, with a landed value in the order of $130 M (Williams 1997). A large number of vessels (840 in 1995) are licensed to operate in the Queensland east coast otter–trawl fisheries. The prawn trawl fishery in the northern GBRMP is a mixed–species fishery with tiger prawns (Penaeus semisulcatus and P. esculentus), king prawns (Penaeus longistylus and P. latisulcatus) and endeavour prawns (Metapenaeus endeavouri and M. ensis) predominant. Moreton Bay bugs (Thenus orientalis) can be a significant bycatch. Local aggregations of particular species combinations are common along the coast, both seasonally and spatially. Most of the fishing is to the west of the Barrier Reef, although king prawns and scallops are also fished in near–reef and inter–reef grounds on the western edge of the GBR. The king prawn fishery (P. longistylus) is expanding into inter–reef areas in the central and northern GBR.

The fishers maximise their returns by sequential exploitation in different parts of the GBRMP according to the catch rates of particular species. A major factor affecting the management and understanding of these trawl fisheries is the degree of mobility of the participating vessels. In addition, the spatial structure of the fisheries is changing as navigation improvements enable more accurate positioning of trawlers. These changes in the fisheries expose a larger area of the GBRMP to trawling and bring trawling operations closer to the reef systems.

1.4 GBRMPA and prawn trawling

Part of GBRMPA's brief is to oversee the management of commercial and other fisheries in the Marine Park to the extent necessary to meet the objectives of the Act. The main commercial fishery in the GBR is prawn trawling. GBRMPA recognises that prawn trawling has a long history in the region, and considers that it is consistent with the multiple–use status of some areas. However GBRMPA also recognises that trawling affects target species, non–target species and the habitat, and hence could affect the ecology of both the fished areas and the reef system as a whole. To fulfil its statutory responsibility GBRMPA must determine whether these effects are consistent with "reasonable use" of the GBR and, if not, how the activities should be modified to be consistent with the Act. GBRMPA can control fishing by applying zoning restrictions, even though fisheries management remains the responsibility of the relevant State departments.

The presence of a major prawn and scallop fishery in the Great Barrier Reef (GBR) World Heritage Area has raised questions about the possible impacts of trawling on the inter-reef fauna. The GBR extends for some 2000 km along the East Coast of Queensland and encloses a continuous lagoon between the Reef and the mainland. Trawling originally took place mainly in this lagoon. Since the early 1980s, it has been occurring closer to and between the individual reefs of the GBR in order to target red spot king prawns (Penaeus longistylus), a species that is associated with coral reefs. Modern navigational equipment — especially improved high resolution echosounders, Global Positioning Systems (GPS) and associated plotters — is making it possible to trawl nearer to reefs and to avoid ground that would snag nets. According to Alongi (1989) in the cental GBR region, the inner continental shelf out to around 20-m depth in the lagoon, has a substrate of fine terrigenous mud and quartz sand with low epifaunal diversity, dominated by bryozoans and echinoderms. The middle shelf consists of carbonate sediments and has an abundant and diverse epifauna dominated by echinoderms, bryozoans, large ascidians, sponges and large foraminiferans. Concerns about the possible effects of trawling in this latter region led the GBR Marine Park Authority (GBRMPA) in 1989, to organise a workshop on research into the effects of fishing in the GBR region. The workshop identified the effects of trawling as a major research issue for the agencies concerned with the management of the GBR Marine Park. The workshop recommended that a study into the effects of trawling should take advantage of a large area closed to trawling (Marine National Park B Zone) in the Far Northern Section of the GBR (Craik et al, 1989). This closure, commonly referred to as the Green Zone, is a cross-shelf strip of approximately 10 000 km2. It includes the inshore lagoon, inshore reefs and islands, mid–shelf shoal and reef zone and offshore lagoon, and is bordered to seaward by the outer barrier ribbon reefs.

The GBRMPA views trawling as the most controversial type of commercial fishing. The size and apparent catching power of vessels makes trawling a highly visible activity in the eyes of the public, and trawling is often perceived to be an indiscriminate method of fishing. The GBRMPA frequently receives statements expressing concerns about the impact of trawling and the future of trawling in the GBR region.

1.5 Magnetic Island workshop on the effects of prawn trawling

In response to these concerns GBRMPA convened a scientific workshop in February 1989 at Magnetic Island under the auspices of the Advisory Committee on the Effects of Fishing in the Great Barrier Reef Region, to discuss and recommend a research program on the effects of fishing, particularly trawling, in the Great Barrier Reef Region (Craik, 1989).

The specific objectives of the workshop were to:

1. bring together information on fisheries in the Great Barrier Reef Region;

2. bring together information on near reef and inter–reef biota of the Great Barrier Reef;

3. identify ways in which fishing could affect the Great Barrier Reef Region;

4. recommend and prioritise future research in relation to the effects of prawn trawling in the GBR.

Research findings relating to the effects of fishing in the Great Barrier Reef Region were presented. Existing knowledge and information gaps were identified and summarised for each subject area.

The workshop concluded the following:

1. from studies of the prawn fisheries of Torres Strait and central Queensland, there is little evidence of any direct effects of prawn trawling on reef communities;

2. studies of the bycatch of the Torres Strait and central Queensland prawn fisheries suggest that coral reef fish species are uncommon in the catch of prawn trawlers;

3. studies of the fate of the prawn trawl bycatch in the Torres Strait show that most of the discards of prawn trawlers are dead when returned to the ocean and are consumed by birds, sharks, dolphins or bottom fish;

4. studies of the impact of trawling on fish communities in the Torres Strait, Gulf of Carpentaria and the North–West Shelf demonstrated it has significant effects on the fish on the trawl grounds by decreasing the density of bottom–dwelling species, and increasing the density of predatory and mid–water species;

5. comparisons of benthic communities of areas open and closed to trawling in the Torres Strait and central Queensland suggest prawn trawling has a significant affect on benthic communities by decreasing the biomass of epibenthic animals and plants on the trawl grounds;

6. apart from studies of the distribution of the benthic communities in parts of central Queensland, little is known about the inter–reef benthic animal and plant communities of the GBR, the effect(s) on the system of their removal, or the recovery rate of these communities if trawling ceased;

7. discards may have significant effects on seabird populations;

8. the impact of fishing on GBRMP is not known because there have been so few studies of the effects of fishing (prawn trawling and line fishing) on the GBR;

9. the effects of fishing on the GBR is a major issue for the agencies concerned with the management of the GBRMP.

1.6 Recommendations from the 1989 Workshop

The workshop recommended that a high priority should be given to studies of the effects of fishing on the GBR. In particular, an experimental study of the effects of trawling should be undertaken, taking advantage of the area closed to trawling (Marine National Park B) in the Far Northern Section of the Great Barrier Reef Marine Park. The workshop considered such a project vital to achieving the objectives of monitoring and maintaining the resources of the Great Barrier Reef Region.

CSIRO, in collaboration with QDPI, developed a five–year project entitled "The Environmental Impacts of Prawn Trawling in the Far Northern Section of the Great Barrier Reef". The project entailed a number of different sampling/experimental procedures, each designed to address one or two specific issues identified by the Magnetic Island workshop. Funding was provided primarily by GBRMPA, with contributions from the Fisheries Research and Development Corporation (FRDC) and from CSIRO. The project began in 1991/92 and the fieldwork ended in 1995/96. In agreement with GBRMPA, production of the Final Report was scheduled for 1996/97.

1.7 Scope of the project into the Effects of Trawling

The project described in this report has provided information on the following topics:

1. a quantitative description of the physical environment, sediment characteristics, fishing effort, fish communities, epibenthic communities and prawn populations of the Far Northern Section Cross–Shelf Closure and areas to the north and south—presented in Chapter 2;

2. a comparison of the fish, benthic and prawn communities of areas closed to trawling with areas open to trawling—presented in Chapter 3;

3. an assessment of the impact of prawn trawling on benthic communities and fish communities—presented in Chapter 4 (BACI experiment) and Chapter 5 (Repeat trawl experiment);

4. a quantitative description of the composition of bycatch produced by prawn trawling in the Green Zone and the areas to the immediate north and south of the Zone, presented in Chapters 2 and 6;

5. a list of the species of trawled animals (vertebrates and invertebrates) other than prawns returned to the sea and whether they float or sink, and quantification of the fate of the dead material—presented in Chapter 6;

6. quantitative estimates of the importance of trawl discards in the diets of seabirds, the degree of dependence on such discards and the effects of discards on seabird populations—presented in Chapter 6.

This report has been structured in the following way. The summary presented an overview of the findings of the project and their implication for management of the GBR and for prawn fisheries on the east coast of Queensland. Chapter 1 has provides a general introduction. Chapters 2 to 6 contain the scientific findings of the project (methods and results for each major topic, together with a more detailed introduction). There are up to three components for each of these chapters: the text and tables of primary interest; all figures; appendices containing supporting documents and tables of secondary interest. Chapter 7 presents the major findings and implications for management; a model which synthesises our knowledge of the impact of trawling on epibenthic faunas; a commentary on the east coast trawl management plan in the light of the findings of this study; the aspects of the 1989 Workshop that have been addressed by the project and finally it identifies the flow on research from the project. Chapter 8 contains a list of references used in this Final Report and the various reports that were generated during the project.

CHAPTER 2

DESCRIPTION OF THE STUDY AREA

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2 DESCRIPTION OF THE STUDY AREA

2.1 Introduction

Objective

To describe the study area in the Far Northern Section of the Great Barrier Reef (GBR) Marine park, its geographical location, the physical attributes of the region, the fishing effort within and adjacent to it, and the composition and distribution of its demersal flora and fauna.

The Great Barrier Reef Marine Park extends seaward from the coast of Queensland for a distance ranging from 80 to 200 km and covers a total area of approximately 348 700 km^2.

The Marine Park is divided into four sections. The Far Northern Section of the Marine Park extends from 10°41'S, 145°00'E to 15°00'S, 145°00'E. Within this section of the park a cross-shelf area-Closure of approximately 10 000 km^2 was declared and zoned as the "Far Northern Cross-Shelf Closure Area", also referred to as the Cross-Shelf Closure or "Green Zone" (Figure 2.01). It is closed to all fishing.

The Closure includes the inshore lagoon, the inshore reefs and islands, the mid-shelf shoal and reef zone and the offshore lagoon, and is bordered to seaward by the outer barrier ribbon reefs. The Closure could be broadly stratified according to these habitat types, but, within a strata, micro-habitats make up a complex mosaic according to sediment type (Section 2.3), depth (Section 2.4), turbidity and three-dimensional structure of corals, sponges and other megabenthos.

The Cross-Shelf Closure was established in 1985. The original intention of setting up a large, remote-area Closure was to provide a reference and conservation zone encompassing coastal to outer shelf habitats that would enable future research at a scale large enough to understand coral reef ecosystem dynamics (GBRMPA 1985). In particular, the Closure provided an area away from heavily exploited sites for assessment of the impact of fishing on the ecology of complex tropical marine ecosystems.

Despite being closed to fishing, illegal fishing has taken place in the study area. This is described in Section 2.5 which presents knowledge of trawling since the Cross-Shelf Closure area was declared and compares it with other regions of the Great Barrier Reef. An assessment of the probable distribution and intensity of illegal trawling within the Closure area is also given in Section 2.6. The relative efficiencies of fish and prawn trawls for sampling the fish communities were assessed and the results of this comparison are presented in Section 2.7.

CSIRO and QDPI conducted two surveys, the first in 1992 and the second in 1993. The first survey provided a description of the biological communities and the second compared zones that were open and closed to trawling. We combined data from 1992 and 1993 for the data analysis reported in chapters 2 and 3. The strong advantage in doing so is that the large combined data set provides a more powerful tool for assessing cross-shelf variation in the biological communities. We focus in this chapter on cross-shelf variations rather than other effects such as differences between zones open and closed to trawling because that is dealt with in chapter 3 and it is by far the most dominant component of variation. Section 2.8 presents a description of the marine fauna and flora inside and adjacent to the Cross-Shelf Closure, as sampled by the prawns and bycatch from the prawn trawler and fish from the fish trawler and the invertebrates in the benthic dredge. Finally, Section 2.8 assesses distribution patterns of all trawled species. The results of these two surveys will form a baseline for further studies of an area for which little information exists. The area is unique in that it represents a transitional area between the Torres Strait and the GBR, and is the longest stretch of coastline without a major river system in the GBR region (Harris 1990).

2.2 Physical environment

Weather Patterns

2.2.1 Basic Summer Patterns

The northern Coral Sea is within the tropical climate region that has pronounced summer rainfall and relatively dry winters, and is subject to both the trade winds and tropical monsoon air masses.

The northern Coral Sea is under the influence of the 'Tropical Maritime Pacific (pTm)' and the 'Equatorial (Em)' air masses (Tapper and Hurr 1993). The warm pTm air mass, which has its source in the tropical western Pacific Ocean and is driven by the trade winds, affects the North Queensland Coast most of the year and can bring heavy rainfall if associated with a tropical cyclone. The very warm, moist and unstable Em air mass, which has its source in the maritime area to the north and west of Australia, only affects the northern Coral Sea in summer in association with the north-west monsoon. It brings extremely heavy rainfall and high humidity to the area, and, during very active monsoon seasons, can affect areas as far as 30°S latitude.

In summer, the north of Australia is mostly occupied by a complex set of low pressure systems (Figure 2.02). The commonest pattern has two heat lows over the north of the continent. The western low (the stronger and more consistent of the two) is called the Pilbara low and the eastern low is called the Cloncurry low because of the positions that they commonly occupy over Australia. The area of low pressure over the continent is important because it brings moist air masses onshore: the north-west monsoon flow with its Em air mass from the north, and the recurved trade winds with their pTm air mass from the Pacific Ocean. The recurved trade wind flows are deflected by the Cloncurry low to become the north-easterly winds on the north-east coast. This effect is felt as far north as Cooktown. At Thursday Island the monsoon has a strong effect. During the November to March period, low-level westerly winds are more frequent (40%) than south-easterly winds (<15%), but they are very shallow.

2.2.2 Basic winter patterns

In winter the subtropical ridge of high pressure now lies at 25°S to 30°S latitude (Figure 2.03) The interior of the continent is cool, and heat-induced low pressure cells are generally absent.

North of the subtropical ridge there is a steady south–easterly trade wind flow over a dry, warm and virtually cloud-free continent. Much of northern Australia is under the influence of the 'dry season', which normally lasts from April to November. Because the trade winds with their moist pTm air mass tend to blow parallel to the coast, they are not lifted orographically and produce little rainfall. The whole of the Coral Sea is subject to the trade winds, which are the most frequent type of wind (over 80% of all winds) at Thursday Island.

2.2.3 Weather patterns in the Cross-Shelf Closure

There are no weather sites in the study area. The nearest weather sites are on Thursday Island and at Lockhardt River. At Thursday Island about 60% of winter storms are from the south-east and 40% are summer monsoons from the north-west. About 33% of the monsoonal storms are associated with the passage of tropical cyclones to the south of Thursday Island. Most of these cyclones move from the Gulf of Carpentaria to the south or east into the Coral Sea. Data on the occurrence and position of cyclones were obtained from the National Climate Centre database, Melbourne.

2.2.4 Occurrence of cyclones in the study area

Only 22 cyclones were recorded between 9° and 16°S and 142° and 146°E from 1975 to 1995. Of these, only two (both in March 1984) were in the Cross-Shelf Closure (11–12°S), while eight were in the Lizard Island area (14–15°S); (two in January 1979, two in February 1981, one in April 1982, one in April 1986 and one in March 1990). No cyclones were recorded in the region in 1980, 1983, 1987, 1988, 1993, 1994 and 1995 (National Climate Centre, Data Services Section).

2.2.5 Wind patterns during the CSIRO/ QDPI sampling cruises

Wind speed data was obtained from the weather bureau for Thursday Island (about 100 km north of the study area) and Lockhardt River (situated about 60 km to the south of the study area). The data was plotted for the periods of the sampling cruises (Figure 2.04). The weather data at both these sites was collected up to 8 times per day (3-hourly). During 1994 and 1995 only two readings per day (0900 h and 1500 h) were given for each station. The wind speed for Thursday Island was nearly always higher than for Lockhardt River; but not always as high as the winds experienced offshore in the study area during our cruises.

The south-east trade winds predominated (73% to 91%) for each of the cruises except during February and March 1995, when the wind was 100% from the north-west. This unusual pattern was due to the presence of two cyclones: one (Warren) in the Gulf of Carpentaria and the other (Valerie) in the Coral Sea. The combination of these two low pressure systems resulted in constant 30 knot winds and a squall of up to 50+ knots from the north-west, accompanied by driving rain.

During the first survey cruise the wind was mainly from the south-east (91%) and averaged around 18–20 knots (Figure 2.04a), 7% was from the east and 2% from the north-east. For the second survey cruise the wind was mainly (85%) from the south-east (15–20 knots) and 15% from the north-west (5-10 knots) (Figure 2.04b). At the start of the BACI experiment the wind was mainly from the south-east (79%) at 15 to 20 knots and for several days was around 30 knots (Figure 2.04c). During March 1994, the winds were from the south-east (73%) at less than 15 knots (Figure 2.04d). The final cruise for the BACI experiment was impeded by the presence of two cyclones, but this is not reflected in the wind data for the two weather sites except that the wind was 100% from the north-west. (Figure 2.04e). The long distance from ports, the almost constant wind coupled with the mostly uncharted nature of the study area, combined to make this a challenging research site.

2.3 Sediments and carbonates

2.3.1 Introduction

A comprehensive sediment sampling program was carried out during this study because sediment type has been shown to affect the distribution of animals living on or near the sea bottom in tropical areas (Fisk 1983; Jones 1984; Sommers 1987, 1994; Chevillon and de-Forges 1988; Long and Poiner 1994). In this report the distribution of sediments in the study area is presented in much greater detail than in prior, larger scale studies such as those of Maxwell (1968, 1973) and Furnas et al. (1990). This detailed sediment information provides a basis for understanding the distributions of the fauna examined in other elements of the joint project. We also present a bathymetry map compiled during our surveys.

2.3.2 Methods

Because sediment type has been shown to affect the distribution of animals living on or near the sea bottom in tropical areas (Fisk 1983; Jones 1984; Sommers 1987, 1994; Chevillon and de-Forges 1988; Long and Poiner 1994), a comprehensive sediment sampling program was carried out during this study and these data were used to analyse distributions of the fauna.

Surveys were conducted in 1992 and 1993 to describe and compare the fauna of the Green Zone and adjacent areas. Both surveys used two vessels, the commercial fish trawler *Clipper Bird* and the research prawn trawler *Gwendoline May*. Sediment samples obtained by *Clipper Bird* were collected either by using a 0.01 m² van Veen grab or by divers . All samples obtained by the *Gwendoline May* were collected using a sediment dredge as described in McLoughlin and Young (1985). Sample sites were distributed at random throughout the area (Figure 2.05a) as determined by the biological sampling regime; the position of each site was obtained by using the Global Positioning System. For the purposes of sampling design, the area was divided into 5 strata (Figure 2.05a). The strata represented habitats identified within the area: inshore lagoon (A); inshore reefs and islands (B); inshore reef-shoal matrix (C); offshore reef-shoal matrix (D); outer lagoon (E). Strata A and B are referred to as "inshore", and C, D and E as "offshore".

Samples for sediment and carbonate analysis were collected during the 1992 and 1993 cruises. The *Clipper Bird* and *Gwendoline May* research cruises collected sediment for particle analysis (137 sites, Figure 2.05a) and the *Clipper Bird* samples were also used for carbonate analysis (81 sites, Figure 2.05b)).

Particle size analysis of the *Clipper Bird* samples (at Cleveland) employed the Folk (1968) method as modified by McLoughlin and Young (1985). A representative subsample was dispersed in 1% calgon solution and washed through a 0.063 mm mesh to separate the mud component. The gravel and sand fractions were then mechanically sieved through a standard Endecott sieve nest of 2.0, 1.0, 0.5, 0.25, 0.125, 0.063 mm mesh. All fractions were dried and weighed. Particle size analysis of the *Gwendoline May* samples (at Cairns) used a Malvern Instruments Mastersizer (Version 1b). This instrument obtained a measure of particle size distribution using the diffraction properties of a laser beam passed through a particle suspension. The distribution of particle size was expressed as a percentage of 32 fractions between 0.0018 mm and 2.0 mm. These data were grouped to the same size classes as the Endecott sieve data for all our analysis. Samples were grouped according to cross-shelf strata, the fractions were then averaged and the resultant distributions were tested for difference using a Kolmogorov Smirnov test. Ternary diagrams were made for each of the strata showing the relative composition of mud, sand and gravel. Maps showing percentage particle size distribution were made for mud, sand and gravel to show differences in substrates between the strata. Carbonate content was calculated as weight loss after the sample was digested with 1.0 M hydrochloric acid (after McLoughlin and Young 1985).

2.3.3 *Results*

Ternary diagrams showed that stratum A consists of a mixture of mud (30%) and sand (65%) (Figure 2.06). Stratum B has a nearly even composition of mud (45%) and sand (48%). Stratum C is similar to stratum A with mud (25%) and sand (67%). Stratum D is very sandy (78%) with gravel (12%) while stratum E is also sandy (68%) but with more gravel (22%). For each stratum the mud, sand and gravel percentage composition add up 100%.

The relative distributions of the mud, sand, and gravel are shown on the maps (Figure 2.07). The mud fraction was dominant in a narrow band in the middle of the inshore lagoon (mostly strata B, Figure 2.07a). Sand was the dominant sediment fraction (>50%) through most of the area (Figure 2.07a) with the highest percentages close to the coast and over the shoal region. The gravel component was very low (<20%) over most of the area with more gravel content in the eastern shoal and the outer lagoon regions (Figure 2.07b).

The stratification of sediment was longitudinal as is shown in Table 2.01. There was no significant difference ($p < 0.05$) in the proportion of sediment fractions when the latitudinal areas north, within and south of the Green Zone were compared. However, when adjacent longitudinal strata were compared significant differences were found between strata B, C and D.

Table 2.01 Two-tailed Kolmogorov Smirnov test of distribution of sediment particle size for adjacent areas within the study site in the Far Northern Section of the Great Barrier Reef.
NS, not significant at $p < 0.05$

Areas compared	Number of samples	p-value
North of Green Zone vs Within Green Zone	62, 134	NS (1.0)
Within Green Zone vs South of Green Zone	134,48	NS (1.0)
Stratum A vs B	51, 56	NS (0.12)
Stratum B vs C	56, 47	0.0275
Stratum C vs D	47, 53	0.0013
Stratum D vs E	53, 39	NS (0.7357)

Microscopic examination of the sediment fractions greater than 0.5 mm in diameter showed that there was a contribution from terrigenous and molluscan material near the coast (Stratum A), grading to molluscan and foraminiferal sediments in Stratum B, foraminifera were dominant in Stratum C and Halimeda remnants dominated offshore areas (Strata D and E).

Carbonate values ranged from 30.2% to 99.2%, with a mean percentage value of 83.17%. Sediment carbonate values were low close to the coast and high in offshore areas with a steep increase (50% rising to 80%) on the boundary between Strata A and B (Figure 2.07b). The relatively low carbonate values in Stratum A indicate that the sediments were mainly terrigenous in origin and the high values in the other strata show that the sediments were mainly biogenic in origin.

2.4 Bathymetry

2.4.1 Introduction

Because much of the study area was uncharted we constructed a bathymetry map to demonstrate the complexity of the sea bottom. We also used the depth data in the analysis of the distribution of the biota. During the surveys of 1992 and 1993, depth soundings were recorded at nearly all sites sampled by the fish trawler. Data was also collected from between the sites. Both GPS position data and depth data were logged onto a computer at two second intervals. The areas covered in these cruises included all cross-shelf strata from the inshore lagoon (Stratum A) to the outer lagoon (Stratum E), in the Green Zone and the adjacent open area (Figure 2.05).

2.4.2 Methods

A digital bathymetric and elevation model (DBEM) was generated from measurements collated from several sources including the AUS836 and AUS835 navigation charts, observations collected by CSIRO, and terrestrial spot heights.

The DBEM was generated using the topogrid tool in ARCinfo. This is an implementation of an Australian National University Digital Elevation Model (ANUDEM) program developed by Michael Hutchinson (1988, 1989). The method uses an iterative finite difference interpolation technique. It is optimized to have the computational efficiency of 'local' interpolation methods such as inverse distance weighted interpolation, without losing the surface continuity of global interpolation methods such as kriging and splines. It is essentially a way of partially overlaying a number of thin layers with all edges overlapping to form a mozaic – a 'discretised thin plate spline technique' (Wahba, 1990), where the roughness penalty has been modified to allow the fitted digital elevation model to follow abrupt changes in terrain. The resulting surfaces were than range sliced with depth elevations classified into colours and draped as a three dimensional perspective view from 15° above the horizontal (see the view at the front of the report).

2.4.3 Results

A digital depth map is given in Figure 2.08. The depths in the inshore lagoon (Stratum A) range to a maximum of 40 m. The inshore reef (Strata B and C) is an area of flat bottom with platform coral reefs rising steeply from depths of 25–35 m. This area comprises a reef shoal matrix (olive shaded area in Figure 2.07) with high points about 10–15 m below the water surface. In places on the western margin of Stratum B there are small coral reefs with cays emerging above the water line.

The shoals in strata C and D are separated by channels that generally run in a north-west to south-east direction. These channels range in depth from 30–70 m, and were identified by Maxwell (1968) as being part of a "pre-recent drainage system".

The offshore lagoon (Stratam E) runs north-south and is generally uniform in depth (20 - 30 m), but reaches depths of over 200 m near Raine Island. The lagoon (Stratum E) is bordered on the eastern margin by the outer barrier reefs, beyond which the depth rapidly increases. The coral reefs are on the edge of the continental shelf. (see the view at the front of the report).

2.4.4 Discussion

Depths in the study area are similar to depths in the commercial trawling grounds off Townsville—13–60 m (Watson and Goeden 1989) and Torres Strait—15–30 m (Wolanski + Ruddick 1981). The continental shelf, coastline and isobaths all run roughly north–south, and the depth gradually increases from inshore to about 40 m offshore near the barrier ribbon reefs. These ribbon reefs come close to the surface and act as a barrier to water flow from the deep ocean (>1000 m) to the lagoon between the reef and the mainland. The mid reef shoals form a complex matrix of steep sided plateaus that rise from about 35 to 40 m up to about 15-25 m below the sea surface.

The sediments of the study area are coarse grained, mostly biogenic in origin and high in carbonate content, with the exception of a narrow band of sediment close to the coast that has a terrigenous origin. The inshore sediments are finer than those found offshore and contain a greater fraction of mud. The offshore sediments contain a greater fraction of carbonates than the inshore sediments, with resultant clearer waters. This is different from the Princess Charlotte Bay area to the south (latitude 14° S), which has a similar bathymetry. In Princess Charlotte Bay the terrigenous influence is much greater, with large areas of pure (>90%) terrigenous mud (Frankel 1974) and a lower carbonate content (Torgensen et al.

1983). This is due to the input of fluvial sediments from the Kennedy–Norman river system (Sahl and Marsden 1986). The study area lacks fluvial input (Harris 1990) and thus there is little terrigenous sediment available for cross-shelf transport.

The stratification of sediment in the study area has been recognised by Furnas et al. (1990) as a general inshore–offshore gradient of fine to coarse sediment and a corresponding increase in carbonate content. This study allows the stratification to be shown in greater detail than previously.

Although strata A and B showed no significant difference in particle-size distribution, the sharp increase in carbonate at the border between the strata reflects the different origins of the sediments and allows them to be distinguished.

The only strata that are not separable by sediment are D and E, which share similar particle-size distribution, carbonate content and a dominant contribution to the sediment by *Halimeda* remnants. *Halimeda*'s large contribution to sediments in the outer reef area is well documented (Drew 1983; Marshall and Davies 1988; Tuthope and Scoffin 1988). Large *Halimeda* beds in the area of Raine I. have been reported by Wolanski (1990), and extensive beds were seen on underwater video and by divers in the outer lagoon area during the study. It is possible that this large *in situ* contribution by *Halimeda* has caused the similarity in sediments of strata D and E.

The *in situ* formation of sediment probably occurs in the inshore areas as well. Tuthope and Scoffin (1988) found that the sediments of the mid-shelf area near Townsville, dominated by foraminiferal material, were formed *in situ*. The contribution by molluscs to the sediments of the northern region of the GBR is considered by Maxwell (1973) to be from deposits of relict shoreline shell gravels. Thus it is likely that the foraminiferal (strata B and C) and molluscan (strata A, B and C) dominated sediments are autochthonous. The *in situ* formation of sediment could be maintained by the currents in the area. The currents are mainly wind driven with a small tidal influence (Wolanski and Ruddick 1981). These wind-driven currents are longshore and in a northerly direction, except in the monsoon season (December–March), when the currents are southerly (Harris 1990). This current regime would maintain the longitudinal stratification of the sediment because there would be little cross-shelf transport.

Maxwell (1973) found that the carbonate content is probably the most significant parameter of shelf sediment because it differentiates the broad facies pattern of the GBR. The transition from low to high carbonate sediment found in this study was closer to the coast than that found by Furnas et al. (1990). This is due to a difference in methodology: Furnas measured the carbonate of the mud fraction, whereas in this study we measured carbonate from the whole sample, therefore including the high carbonate biogenic fractions of the sediment.

The stratification of sediment in the study area and the dominance of high carbonate sediments is probably caused by the *in situ* formation of sediments derived from biological material. Whether this stratification has any influence on the distribution of the fauna is yet to be determined, although carbonate content of sediments has been shown to affect prawn abundance (Branford 1981).

2.5 Fishing effort

2.5.1 Introduction

Fishing, both commercial and recreational, is the major extractive activity within the Great Barrier Reef Marine Park. The most visible and controversial fishing activity in the eyes of the public is prawn trawling, which consists of over 870 licensed boats (Sainsbury and Poiner 1989). The GBRMPA acknowledges that the harvesting of fish, prawns and other living resources is an established use of the Marine Park. However, GBRMPA also recognises that fishing and trawling affects target species, non-target species and habitat (Craik 1991). Trawling in particular is thought to have the potential for producing ecological effects in both the trawled areas and the reef system as a whole.

Entry to the Queensland east coast prawn trawl fishery is limited, but currently 870 boats are licensed and they have the right to fish in any fishing zone along the 2 000 km of coast. The Great Barrier Reef section of the coast is included in the Great Barrier Reef Marine Park and fishing is restricted to certain areas according to the GBRMPA zoning plan. The fishery in the northern section of the Great Barrier Reef is also subject to an approximately two and a half month seasonal closure from mid-December till March. Nets are restricted to 50 mm diagonal stretch multi-filament mesh with a maximum of 20 fathoms (36.6 m) headline length; usually configured as four 5-fathom nets (Quad-gear). Otter trawl (bottom trawl) gear using ground chain is standard. The average size of trawlers in the fleet is relatively small at 17 m waterline length, with a size limit of 20 m. Most of the trawl grounds are located in the lagoon of the Great Barrier Reef, within 30 km of the coast. The commercial catch is separated according to buyers' categories, which may contain more than one species, see Table 2.02.

Given an average trawl speed of 3 knots and assuming 65% spread of the 20 fathom nets, the swept area for a typical trawler would be approximately 44 035 m^2 or 4.4 ha per hour (swept area method, Sparre et al 1989). Assuming trawling continues for eight hours per night (referred to as a "boat-day" in the logbook database) then 35 ha can be swept per boat-day of fishing effort. Usually this would include a number of passes over the same area of sea bottom.

Both historic and current logbook records were analysed for trends in species composition and catch/effort. The historic records are part of a Queensland Department of Primary Industries (QDPI) and QFMA project to obtain and collate catch and effort records from the period prior to the introduction of compulsory trawl logbooks in 1988. The sources for the data were personal diaries and voluntary logbooks that had been kept by trawler skippers for their own use. Such records can go back over 20 years and, in most cases, were presented to QFISH after a trawler skipper had retired.

The current QFISH logbook program is compulsory and covers the whole trawl fleet, with a 95% level of compliance (Neil Trainor, QFMA, personal communication). QFISH logbooks are organised on 30' latitude by 30' longitude grids. In the case of the Green Zone, the QFISH grids in the 11°00' to 12°00' latitudinal band overlap the fished areas to the north and south, and the Green Zone itself (Figure 2.09). The actual area that can be legally fished is only 35% of the total area of these grids.

Table 2.02 Major commercial categories and scientific names of prawn (shrimp) species targeted by the Queensland East Coast Prawn Trawl fishery

Category	Common name	Species
Tiger	Brown tiger prawn	*Penaeus esculentus*
	Grooved tiger prawn	*Penaeus semisulcatus*
King	Red spot king prawn	*Penaeus longistylus*
	Blue leg king prawn	*Penaeus latisulcatus*
Endeavours	True Endeavour prawn	*Metapenaeus endeavouri*
	False Endeavour prawn	*Metapenaeus ensis*
Banana	Banana prawn	*Penaeus merguiensis*

The majority of commercial prawn species are caught at night, but there is a daylight inshore fishery for banana prawns. Average number of boats, average days fished, and average length of shot, are given in Table 2.03 for each half degree band between 11°00' to 15°00'S, encompassing the Far Northern Section of the Great Barrier Reef Marine Park.

Table 2.03 Summary description of the activity of commercial trawlers for 1988–1993, for each half degree latitude band between 11°00' and 15°00'S, encompassing the Far Northern Section of the Great Barrier Reef Marine Park

Band	Average boat-days (per year)	Average boats (per year)	Average shot (hours)	Area
11° 00'	1831	109	} 2.51	North of Green Zone
11° 30'	1290	121		South of Green Zone
12° 00'	747	101	} 2.57	
12° 30'	1885	141		
13° 00'	1410	143	} 2.66	
13° 30'	2130	157		
14° 00'	5323	204	} 2.60	Princess Charlotte Bay
14° 30'	1871	134		Princess Charlotte Bay

Note 1. Source, QFISH logbook database (QFMA Brisbane). Latitude given refers to the upper left-hand corner of the band.
Note 2. The average shot duration was calculated for each degree of latitude.

2.5.2 Analysis of logbook data for Far Northern Section

Historic Catch and Effort Logbook Records

Table 2.04 summarises the available historic logbook data from 11°00' S to 12°00' S, which encloses the Far Northern Section Cross-Shelf Green Zone area. These data do not include all boats fishing in the area as the logbooks were voluntary at this time. A steady increase from 1980 to 1988 in the number of boats and days fished was apparent.

Based on the number of boats reporting in 1988 (Table 2.05), when logbooks were first made compulsory, compared with those reporting in 1987, it would appear that Table 2.04 data represents 20% of the boats fishing in the Far Northern Cross-Shelf Closure prior to 1988. From anecdotal evidence and experience from past voluntary logbook programs, this percentage was considered a reasonable estimate (QDPI data). In the early 1980s, however, the number of boats reporting would have been much closer to the actual number fishing in what were then "new grounds".

Table 2.04 Prawn trawl catch and effort data for 11°00' S to 12°00' S from 1980–87

Year	Days	Boats	Banana (kg)	Tiger (kg)	End. (kg)	King (kg)	Total (kg)
1980	7	4	0	310	148	20	488
1981	6	4	0	401	301	0	699
1982	25	13	1337	1016	753	58	3125
1983	56	21	0	2310	2131	850	5421
1984	74	24	26	4085	4997	1422	10806
1985	69	19	121	3886	5540	1581	11415
1986	424	37	128	16120	47939	9369	74004
1987	583	46	79	23086	57402	20830	101656

Source AFS and QFISH historic trawl database (supplied courtesy of Neil Trainor, QDPI, Brisbane)

Historical Catch Composition

Historically the following species were trawled within areas of the Green Zone: Tiger, King (Blue Leg Kings plus Red Spot Kings), and Endeavour prawns. Banana prawns were taken irregularly. Over time, there appears to have been a switch from catching predominantly Tiger prawns to Endeavour prawns. This may reflect changes in species abundance due to increased fishing pressure, changes in the market leading to a change in target species, or that trawlers now exploit areas deeper into the inter-reef, hence catching a different suite of prawn species. A similar shift of catch composition over time was observed from other northern sections of the Queensland East Coast, in particular at Princess Charlotte Bay (Coles et al. 1985, 1987). Both the historic logbook data and the 1985 submission by the QFMA/QCFO to the GBRMPA agree on this assessment of the prawn resource of the area.

Based on the logbook data, the amount of fishing per grid in the study area is relatively small compared with Torres Strait, Princess Charlotte Bay and Townsville (Figure 2.10a, b). As expected, most of the effort is concentrated closer to the mainland or protective islands.

Table 2.05 Prawn trawl catch and effort data for 11°00' S to 12°00' S from 1988–93

Years	Days	Boats	Banana (kg)	Tiger (t)	End. (t)	King (t)	Total* (t)
1988	2624	160	48	111	222	45	382
1989	4507	201	178	128	426	74	651
1990	3249	152	429	105	293	52	453
1991	2800	134	473	79	198	68	356
1992	2903	134	39	112	175	69	361
1993	2205	132	—	93	155	32	280

*Source, QDPI/QFMA SUNFISH Logbook database, corrected and updated to 1/1/94 (supplied courtesy of Neil Trainor, QDPI, Brisbane). * Total (kg) includes small quantities of "mixed" species of prawn catch*

2.5.3 Discussion

Prawn Trawling

Fishing effort (prawn trawling) in the Shelburne Bay region is mainly confined to two 30' grids that each overlap the green Zone, one to the north and the other to the south (Table 2.06). There was little effort spent fishing in the grids to the east of these, probably due to the uncharted reefs and shoals within these grids. Fishing effort is lower in the Shelburne Bay region than in the Torres Strait to the north or the Princess Charlotte Bay and Townsville regions to the south, but has a relatively high catchrate per boat for prawns compared with these regions (Table 2.06). This may reflect the smaller effort in the region when compared with other areas or a measure of illegal fishing (Table 2.06). More accurate estimation of the fishing effort in the region is required to improve understanding of the fishing pressure adjacent to the green Zone.

Table 2.06 Estimated fishing effort and catch data for the east and north coast of Australia. The data are interpreted from various sources

Fishing area	Average boat-days year-1	Average Catch boat-1-day-1 (kg)
Torres Strait1	4 350*	135–410
Shelburne Bay2	2 002	146
Princess Charlotte Bay2	7 194	104
Townsville2	7 680	67
Gulf of Carpentaria3	24 927	280

1. Turnbull and Watson (1994) 2. QFISH data 3. Sachse and Robins (1996)
(based on 10 h day for 1994)*

2.6 Illegal fishing

2.6.1 Introduction

It is difficult and expensive to enforce a ban on fishing in such a large and remote region of the Great Barrier Reef Marine Park as the Cross-Shelf Closure (Green Zone) in the Far Northern Section. The low level of surveillance currently provided has raised some concern from managers, scientists and industry over the level of illegal trawling that may be occurring within the Green Zone area. Anecdotal evidence suggested that up to 40 to 50 boats regularly trawled the Green Zone despite the ban on fishing by the GBRMPA. Protection of the Green Zone and deductions based on scientific studies of the area may be compromised if the level of infringement is high and, more importantly, if the location of illegal trawling within the Green Zone is unknown. This section of the report gives a compilation of what information is available on illegal trawling in the Green Zone. Based on this data, we give an assessment of the probable distribution and intensity of illegal trawling within the Green Zone. The resultant baseline information on illegal trawling was factored into the analysis of the ecological effects of trawling, to estimate the true contrast between fished and unfished areas.

2.6.2 *Methods to estimate illegal fishing*

Information on the current level of fishing within the Green Zone is limited and at best fragmentary; principally because such records require admission of illegal activity. Therefore the analysis had to be inferential, using a number of sources that each gave part of the picture (Hunter and Schmidt 1990). The concept is similar to meta-analysis of case study data (Warwick and Clarke 1993): "the combined analysis of a range of individual case-studies which in themselves are of limited value but in combination provide a more global insight into the problem under investigation".

Where possible, the concept of verification from three independent sources was carried through each phase of the data gathering. This methodology follows that commonly used in sociology and anthropology (see Creswell 1994). Primary source material and analysis of that material was subdivided into the three main categories (i.e. triangulation): logbook data, interviews, and overflight and surveillance observation.

2.6.3 *Results*

QFISH Logbook Data

QFISH logbook data are recorded in 30' by 30' grids; in the Far Northern Section grids B5, C5, C6, D5, and D6 overlap the Green Zone (Figure 2.10). As fishing is illegal within the Green Zone, no catch data is available directly, but catch is most likely recorded as coming from the "legal" portion of overlapping grids (see Table 2.06). An average catch per boat of 143 kg per day was recorded from these grids over the 1989–90 period, compared to 104 kg per day over 1990–91 for Princess Charlotte Bay (Kurt Derbyshire, Northern Fisheries Centre, Cairns, personal communication). Catch composition has been reasonably consistent at 20–29% Tiger, 58–68% Endeavour and 12% King prawns. Only small numbers of Banana prawns are taken.

Figure 2.11 summarises the relative distribution of the prawn trawl fishing effort based on only the logbook records that gave 6' by 6' grid position or position in latitude and longitude. Re-analysis at a six-minute scale will give, at best, an underestimate of the true level of illegal trawling (between 5% and 40% of the fleet) but it should give an indication of the pattern of where such trawling occurred.

A distinct edge effect was observed along both the north and south borders and a concentration of effort occurs in the southern section, just outside the Green Zone north of Cape Grenville. There was an apparent corridor of illegal trawling following the north-south navigation channel. There was evidence of improper recording of position as some positions were well inland and others out beyond the continental shelf.

Detailed Logbook Comparison Of Fished Areas On The Queensland Coast

A detailed comparison was performed on the catch effort data for QFISH grids in the latitude 11°00' to 12°00' band, which overlaps the Green Zone, and grids in the 14°00' to 15°00' band, which covers a similar area of Princess Charlotte Bay (PCB), but does not overlap the Green Zone. Research trawls from previous projects (QDPI data) had shown the prawn abundance in the two areas were not significantly different (Gribble unpublished data; Kurt Derbyshire QDPI, Northern Fisheries Centre, Cairns, personal communication).

The total area within the 11°00' to 12°00' band, from the shore to the outer barrier ribbon reefs, is 14 466 km². The area of legally trawlable zones (General Purpose A), is 5 063 km² (or 35% of the total). In PCB, the total area within the 14°00' to 15°00' band, from the outer edge of the inshore juvenile habitat reserve to the outer barrier reef, is 9000 km². All of this is legally trawlable. Table 2.07 details the comparison showing both catch per unit of effort (CPUE) and CPUE adjusted for the area available for legal trawling (CPUEA).

Table 2.07 Comparison of catch and effort statistics between 11° S and 12° S (includes Green Zone) and 14° S to 15° S (Princess Charlotte Bay), taken from the QFISH prawn trawl logbook records

Year	11°00' to 12°00' Boats	CPUE	CPUEA	14°00' to 15°00' Boats	CPUE	CPUEA
1988	160	145	0.0286	278	113	0.0126
1989	201	144	0.0284	275	108	0.012
1990	152	139	0.0275	212	127	0.0141
1991	134	127	0.0251	195	135	0.015
1992	134	124	0.0245	173	120	0.0133
1993	132	127	0.0251	191	125	0.0139

Note. 1. CPUE is in kg per boat per day;
Note 2. CPUEA is in kg per boat per day per km², (taken as the area within the QFISH grids that could be legally trawled).

The higher CPUE in the northern 11°00' to 12°00' band could be partly due to there being fewer boats fishing in this area, hence more prawns per boat. The CPUEA, however, indicates either that either the "General Purpose A" areas of the 11°00' to 12°00' band are twice as productive as the comparable area in the 14°00' to 15°00' band, or that there was significant misreporting of catch that actually came from other areas; most likely from within the Green Zone. In the latter case, almost 50% of the reported catch could have come from within the Green Zone. This would make the two bands equal in productivity, but would also mean that the illegal trawling activity within the Green Zone was extensive.

A rough estimate of the probable level of illegal trawling can be gauged by hypothetically spreading the reported catch over the whole area available in the 11°00' to 12°00' band. Given that the actual productivity is known to be similar between the two bands, then the "extra" 50% of the prawns would have to have come from the 65% of the 11°00' to 12°00' band that is closed. The average yearly catch between 1988 and 1993 for the 11° 00' to 12° 00' band was 414 t (QFISH logbook data), 50% of which may have come from the Green Zone. If Figure 2.11 is taken as an estimate of the area trawled within the Green Zone, then less than half the Closure is actually trawled. Therefore the "extra" 207 t would have been caught from an estimated 4 702 km². This represents a mean of 44 kg/km² and, at the average CPUEA rate observed from the 14°00' to 15°00' band (0.0135 kg per boat per day per km², see Table 2.07), would require approximately 3 260 boat days of illegal trawling.

An alternate hypothesis is that the trawling actually occurred in the legal sections of the QFISH grid as reported in the logbooks, and the high catch rates were caused by prawns moving from the green Zone into the depopulated trawled areas. The process would be akin to continuous replacement of the fished population from an unlimited reserve.

Both may be valid interpretations of the logbook data and need to be verified in the context of interpretations made using other independent sources of data on illegal fishing.

Informal Interview And Submissions

People interviewed consisted of retired trawler skippers, enforcement officers (Queensland Boating and Fishing Patrol), and industry representatives including commercial line fishermen, divers and tourist operators who had long associations with the area. The situation did not lend itself to the use of tape recorders during interviews, but normally both the interviewer and an observer were present during interviews and informal notes could be cross-checked later (see Burgess 1982). All interviews were carried out on the basis that names and identities would be strictly confidential.

The consensus was that illegal prawn trawling has been and is currently carried out on a regular basis, although the major area trawled is limited to the shoreward section of the Green Zone parallel to the north–south navigation channel, with some exploratory trawling for red spot king prawns in the outer northern section of the Green Zone. The following points were made consistently:

1. initially “clearing” had been carried out in “small areas”, which involved dragging chains behind the trawlers to remove coral outcrops and sponges;

2. the weather in the Green Zone tended to “lull”; i.e. if the winds were 25 knots north or south of the Green Zone then winds of 15 knots could be expected within it;

3. good prawns could usually be caught in the Green Zone when other areas were not “firing-up”;

4. usually trawls would be started outside the Green Zone and over-run the southern or northern border (edge effects), but the area around Boydong Island, in the middle of the Green Zone close to the north-south navigation channel, was regularly trawled;

5. a number of operators pointed out that it was legal to transit the Green Zone using the north-south navigation channel and it was normal practice to “dip the nets” while transiting to see what prawn was present;

6. satellite Geo-Positioning System (GPS) has had a profound effect on navigation through the reef, making it possible to explore and exploit areas that previously were untrawlable (in this regard the use of GPS was rated as more important than side-scan sonar).

Estimates of the actual level of fishing effort within the Green Zone varied considerably between interviewees but it appears that approximately 47 boats presently fish the Green Zone on a regular basis. This does not mean exclusively or continually, but that in any year a significant proportion of their catch would come from the Green Zone. The actual number of boats fishing depends to a large extent on how good the catch is in other areas. Some trawler skippers appeared to regard the Green Zone as an insurance policy against a bad season. Unsubstantiated reports suggest that illegal product was being transferred to boats fishing outside the Green Zone to fool inspection and/or logbook records.

Zoning Submissions To GBRMPA

Prior to zoning the Far Northern region of the GBRMP in 1985, submissions were made by the QFMA, QCFO and individuals as to which trawling grounds should be kept open. As part of their argument both the species caught and the condition of trawling grounds within the proposed Green Zone were noted on maps of the area. These were based on industry surveys and common knowledge within the fleet at the time. Since 1985 there has been considerable improvement in navigation equipment, particularly the adoption of GPS by the majority of the northern prawn trawl fleet. Areas marked on the submitted maps as "Rough Ground additional navigation aids necessary" are now trawlable in good weather using the appropriate electronic charts and pre-recorded "waypoints".

Overflight And Surveillance Data

Queensland National Parks And Wildlife Service (Marine Parks) Data

Air surveillance flights were flown only four times annually at irregular intervals. A summary of this data was provided by the National Parks and Wildlife Service (now the Queensland Department of Environment) Marine Parks for trawling activity between 11°20' and 12°00' from the financial years 1989–91. Limitations to this data, apart from its scarcity, are that flights were relatively short, usually covered specific reefs (were not wide-area surveys), and took place in daylight when prawn trawlers usually are not working.

Trawlers made up 66 of the total of 124 recorded sightings within the area covered. Activity ranged from anchored (45), rafted (4), underway (2), trawling (4), and unknown (11).

GBRMPA Surveillance And Coast Watch Overflight Data

Electronic surveillance, using a land based radar station, over a 10 day/night period in late 1991 identified 75 trawlers in the vicinity of the Green Zone, 55 of which were trawling, and 26 of these entered the Green Zone while trawling. Incursions occurred mainly in the southern section continuing for up to 5 km inside the Green Zone. Similar short-distance incursions occurred in the northern sections of the Green Zone. Two boats were observed trawling well inside the Green Zone in the vicinity of Boydong Island.

The triangle bounded by Bird Island, Saunders Reef and Cockburn Reef near the southern border was heavily trawled, as were areas associated with the shipping channels. Over the period of surveillance, trawling activity shifted from the southern border of the Green Zone to areas adjacent to the northern border.

The Coast Watch overflight data has similar limitations to the NPWS Marine Parks air surveillance data, in that the number of flights is infrequent and they only occurred during the day time. Up until quite recently, the Coast Watch undertook two types of overflights: (i) sector/plot and (ii) transect. In the former, the Great Barrier Reef was divided up into a series of sector/plots. A number of sector/plots covered the Green Zone area and, in some cases, such as "Stratum A, North", overlapped into adjacent areas (Table 2.08). More trawlers were sighted in the inner sector/plots while sector/plots in the mid-shelf and outer shelf regions of the Green Zone area had very few or no trawler sightings. Sector/plot "Stratum A, North", which overlaps the Green Zone to the north, had the highest number of sightings. The other inner sector/plots had similar numbers of sightings, including "Stratum A, North Central", which is fully enclosed by the Green Zone.

Flight records from 448 transect overflights, which were carried out during 1990–92 and which overflew the Green Zone area for at least part of the flight, were analysed for trawler sightings.

Within the Green Zone area, a total of 135 trawler sightings were recorded (Table 2.09), but the trawlers' activity was logged as either anchored or underway. No trawlers were observed trawling within the Green Zone. In the Cairncross area to the immediate north of the Green Zone, 361 trawlers were sighted, of which 338 were anchored, 13 were underway, and 1 was trawling, while the activity of 9 was "unknown". Immediately south of the Green Zone, in the Temple Bay area, 520 trawlers were sighted, of which 476 were anchored, 32 were underway, 1 was trawling and the remainder were logged as "unknown".

Table 2.08 Coast Watch sector/plot overflight observation of trawling activity within the Far Northern Cross-Shelf Closure area (Green Zone) area and adjacent areas between May 1990 and May 1994

Sector/Plot	Number of trawlers sighted
Statum A, North	65
Stratum A, North Central	18
Stratum B, South Central	18
Stratum AC, South	14
Stratum B, North	1
Stratum B, Central	1
Stratum CD, North Central	0
Stratum CD, South Central	0
Stratum D, South	0
Stratum E, Central	1
Stratum E, South	1

Note: Sector/plot identifiers have been renamed to roughly correspond to cross-shelf strata identified in Figure 2.05, and North or South relative to the Green Zone

Table 2.09 Coast Watch transect overflight observation of trawling activity within the Far Northern Cross-Shelf Closure area (Green Zone) and adjacent areas between May 1990 and March 1992.

AREA	Total sighted	Anchored	Trawling	Underway	Unknown
Cairncross Is. (North)	361	338	1	13	9
Cross-Shelf Closure	135	111	0	23	1
Temple Bay (South)	520	476	1	32	11

Source: Summary from text reports from Coast Watch to GBRMPA, May 1990 to March 1992. Note: (1) daylight flights only; (2) large numbers of trawlers anchored just outside the northern and southern borders of the Cross-Shelf Closure.

The overflights provided no direct evidence of fishing within the Green Zone, but this was to be expected as the overflights took place during the daylight when trawlers are usually anchored. From the number of sightings made of trawlers within easy steaming distance of the Green Zone, it can be inferred that night-time trawling within the Closure could take place. The direct surveillance observations, although made over a very short period of time, confirm the inference, but give no idea of the scale of the illegal trawling.

Operation Barrier Protection

Joint patrols by NPWS Marine Parks and Queensland Boating and Fishing Patrol (QBFP) were carried out in the Far Northern Cross-Shelf Closure area (Green Zone) on four occasions; 3/4/91 to 12/4/91, 15/4/91 to 24/4/91, 5/10/91 to 14/10/91, and 4/11/91 to 13/11/91. Radar watch and night patrols were performed and "contacts" were observed and plotted to the north and south of the Green Zone along the borders. One trawler was observed transiting the Green Zone, but no offences under the GBRMP Act were detected.

These patrols were essentially public relations/policing exercises with zoning information and charts handed out when vessels were boarded. Anecdotal evidence (i.e., interview data) suggests that the dates of patrols were well known in advance and the progress of the patrol vessel was followed on radar by trawlers in the area.

2.6.4 Discussion

Illegal Prawn Trawling

Historically, areas within the Far Northern Cross-Shelf Closure (Green Zone) were exploited for prawns and, since the Closure was proclaimed, some trawling has continued due to the difficulty in policing the restrictions. The 6' grid analysis of the QFISH logbook data provides the best estimate of the likely pattern of illegal trawling in the Green Zone. The data suggest that the northern and southern borders of the Green Zone were subject to edge effects as trawlers over-run shots started in the adjacent open strata. Considerable illegal trawling happened along the north–south navigation channel and concentrated around Boydong Island. This was also reported in fishers' interviews and was confirmed by direct observation by GBRMPA. Trawling occurred in the northern offshore section of the Green Zone, just below (and continuous with) an area in the open zone that is known from logbook records to hold commercial quantities of red-spot king prawns. The middle and outer areas of the Green Zone were originally inaccessible to trawlers because of "rough ground", but this is probably no longer the case since the general adoption of GPS navigational systems. The central middle section of the Green Zone is likely to have had no trawling; this is far enough from the northern and southern borders to escape edge effects and the Green Zone was proclaimed before the advent of GPS allowed exploitation.

The level of trawling effort in and around the shipping channel within the Green Zone and along its borders appears to be high, possibly as high as in some open areas along the north Queensland coast. The interview information suggests that an estimated 47 boats regularly fish the Green Zone, and, dividing this into the estimated 3 260 boat-days of illegal trawling (derived from the comparison of the logbook data from the Green Zone area and that from Princess Charlotte Bay), suggests 69 days illegal trawling per boat per year. There is an annual seasonal closure of the northern trawl grounds for approximately 90 days, hence 69 days represents 25% of the maximum number of possible fishing days. The trawlers do not fish exclusively or continually in the Green Zone, but a significant proportion of their yearly catch would come from the Green Zone area. This level of non-compliance is consistent with the interview data and is supported both by direct observations made by GBRMPA and by the existence of contemporary charts of the Green Zone showing trawl tracks and potential "hookups" well inside the borders (Gribble unpublished data).

2.7 Impact of prawn trawling on fish communities

This section addresses objective 3:

'List of species of fish caught by prawn and fish trawling and for these species an assessment of the life-history stages and proportion of their populations captured by prawn trawlers derived by comparing the catch of fish and prawn trawls.'

In this study the objective was to estimate the proportion of the total fish community that is caught by prawn trawls in the study area (1992 and 1993). The catch of the fish trawls during the day was compared with prawn trawls at night. We carried out additional fish trawls at night to study diel differences in fish composition. We assessed the species, their sizes and the proportion of the fish community caught by prawn trawls.

2.7.1 Introduction

We assumed that a fish trawl, which is designed to catch fish, would sample fish more efficiently than would a prawn trawl that is designed to catch prawns. Prawn trawls catch large amounts of fish, in the Northern Prawn Fishery about 1.5 t of fish bycatch is discarded by each vessel per night (Pender and Willing 1989). The species composition of fish catches by fish trawls and prawn trawls at the same location have not previously been compared in Australia, although studies have been made of the demersal fish composition from fish trawls (Blaber *et al.* 1990b) and prawn trawls (Jones and Derbyshire 1987; Watson et al. 1990) at different locations. In each of these studies, standard commercial nets were used to catch and describe the fish communities. Each of these net types catches a suite of fish species, but no single net type catches all species in a community. The larger Frank and Bryce fish trawls catch more of the pelagic fish while prawn trawls catch more of the demersal fish. Neither of these nets are as effective as the Church dredge for sampling the small benthic species (Martin et al. 1995).

Demersal fish and prawn trawl nets differ in their design and mode of operation. Fish trawls are linked to the trawl (or otter) boards by long wire bridles (Main and Sangster 1981), whereas prawn trawls have short bridles separating the net from the otter boards (Lorimer and Innes 1969). The bridles on fish trawls act to herd many fish into the net (Ramm and Xiao 1995) and so fish trawls sweep a larger area than the width of the net opening (Main and Sangster 1981). The footrope of the fish trawl net is covered with bobbins or rubber discs to keep the net off the bottom and protect the net from damage. These discs vary in diameter so that there are gaps between the seabed and the net's footrope. Australian prawn trawls have a lower headline height (<2 m) than fish trawls (4–5 m); the headrope is at about the same height as the top of the otter boards (Anon 1980; Kulbicki and Wantiez 1990b). Chains are sometimes fitted in front of and attached to the footrope of the prawn trawl net; these cause prawns to jump off the bottom into the path of the net. These differences are likely to result in fish and prawn trawls catching different species and sizes of fish. Fish trawls are usually operated during the day when catches of fish are higher because fish are closer to the bottom (Blaber *et al.* 1990b, 1994). Prawn trawls are used at night when penaeid prawns are most active (Idyll 1950; Wickham 1967). These diel differences also increase the likelihood of the two nets catching different fish.

2.7.2 Methods

Vessels And Nets

The commercial fish trawler *Clipper Bird*, which has an overall length of 25.9 m and an engine of 432 kW power, was used to deploy a Frank and Bryce fish trawl. The same trawl was used on two occasions by the 66 m long CSIRO research trawler *Southern Surveyor*. This trawl has a 26 m headrope and a 32 m footrope fitted with wire and rubber rollers on 250 mm drop chains. The mesh of the wings is 225 mm stretched mesh, that of the body is 150 mm, gradually tapering to a 100 mm extension, and that of the codend is 50 mm. The net is held open by two steel otter boards (200 cm x 150 cm) weighing about 600 kg each. The spread of the net opening is about 65% of the headline length. Each wing of the net is attached to the otter boards by 30 m bridles and about 10 m of connecting links and chain, which gives a spread between the boards of about 42 m. The spread at the wing ends is about 18 m. The hauling speed of the net along the seabed was kept at about 3 knots (5 to 7 km/h).

The QDPI research prawn trawler *Gwendoline May*, with an overall length of 19 m and an engine of 254 kW power, deployed two prawn nets from a beam through an A-frame at the stern. The nets were Florida Flyers, with an 8 m headrope connected with 0.9 m of 8 mm chain to two standard otter boards (214 cm x 85 cm, steel frame with timber slats) and a steel skid between the two nets. An 8 mm ground chain was suspended from the footrope with about 5 links of chain at each hanging so that the ground chain hung about 200 mm below the footrope. The body of the trawl net consisted of 54 mm stretched mesh, of the codend was of 50 mm stretched mesh. The hauling speed of the net along the seabed was about 2 knots.

Comparison Of Catch In Daytime And Night-Time Fish Trawls

Fish trawls were used during both the day and night as part of the assessment of differences in the species composition between the fish trawl and the prawn trawl. The day–night comparisons were made on a cruise of the *Clipper Bird* in April 1994 (3 sites) and two cruises of the *Southern Surveyor* in November–December 1991 and January 1993. The *Southern Surveyor* cruises sampled the same areas as the *Clipper Bird* and *Gwendoline May*, but only in areas adjacent to the shipping channel. The *Southern Surveyor* nets and procedure for collecting data were identical to those on the *Clipper Bird*, except that sampling was continuous over 24 hours.

On the basis of presence or absence patterns in trawls, each species was classified as catchable by day only, night only or day and night. However, a species that is not very common could appear to be catchable only by day simply because of the limited number of trawls. Therefore, a randomisation test (Sokal and Rohlf 1969) was used to assess whether the number of species found in the day only, night only and day and night classes could have arisen purely by chance. A randomisation test is used to demonstrate whether a single observed data set is significantly different from a series of random rearrangements of the same data set; it is used when the statistic to be computed has an unknown distribution.

The randomisation test was carried out as follows. The method is described for the day-vs-night comparison of fish trawls, but was also used for the comparison of fish and prawn trawls. For each trawl, a vector was set up to reflect the presence or absence of the entire suite of species observed in the study. This produced sixteen pairs of vectors (one day–night pair per station). For each randomisation, the "day" or "night" labels of every pair were assigned at random: in other words, sometimes the "day" and "night" labels were swapped and sometimes they were preserved. Then the "random" data set was used to classify each species as being catchable only by day, only by night or by both day and night. This procedure was carried out 1000 times and a frequency ("randomisation") distribution was constructed for each category. The probability of obtaining results as extreme (low or high) as the real counts from the trawls was noted: a low probability would suggest that the observed frequency of each category is a real rather than a chance effect.

To discern whether fish common to day and night catches had different catchabilities, the weights of each species caught at 7 (chosen arbitrarily in order to obtain data sets that did not contain rare species caught at only a few sites) or more sites were $\log_{10}$ transformed to stabilise the variance and then analysed by an SAS (1989) analysis of variance procedure (mixed model), with estimates for the difference in weights between day and night catches and 95% confidence limits as output for each species. Sites at which a species was not caught in either type of trawl were ignored in the analysis.

Comparison Of Fish-Trawl And Prawn-Trawl Catches

Data for this study were collected from two cruises: one in May 1992 and the other in March–April 1993. In both cruises, each trawler sampled the same sites in the study area over a period of 4 weeks. Tows were of about 30 min duration or about 1.5 n.mile in length. The duration of the trawl was timed from when the trawl warp was fully paid out until the net began to be hauled in. All the fish trawl samples were collected during the day (0630–1830 h) and all the prawn trawl samples were collected at night (1900–0500). At some sites with rough substrata, only the fish trawl could be used. The comparisons in this study are restricted to sites that were sampled by both trawlers.

Total catches, or subsamples if catches were >100 kg, were frozen on board and analysed back in the laboratory. Every specimen larger than ~500 mm was identified to species, measured and weighed and processed on board ship. Whenever a subsample was collected, the remaining catch was weighed and then discarded at sea. The numbers and weights of each species in the total catch were then calculated by multiplying the subsample by a factor (inverse of the proportion of the sample taken), plus the number and weight of all the larger fish that were removed before the subsample was taken. Frequency of occurrence for each species was calculated as the number of sites at which that species was caught.

Catch rates kg h^{-1} (standardised) were compared for species that were caught at more than 7 sites by at least one of the fish or prawn trawls. To discern whether a fish caught by the fish or prawn trawls had different catchabilities, the $\log_{10}$ of the weight of each species was analysed by an SAS (1989) analysis of variance procedure (mixed model). Estimates of differences between the fish and prawn trawls in the weight of catches for each species (with 95% confidence limits) were calculated. Many species caught at only a few sites were not included in the analysis of variance.

Assessment Of Life History Stages

Comparison of length–frequencies of fish caught by fish and prawn trawls
Comparison of length–frequencies of fish caught by prawn trawls in each of the five strata

The length–frequencies (cm size classes) of fish species in the fish trawl and prawn trawl catches were compared when there were at least 30 individuals caught by each type of gear. For teleost fish, the standard length was measured; for sharks, the total length; and for stingrays, the width of the disc. All species except the elasmobranchs were identified to species. Length–frequency distributions for each species were compared by the SAS (1989)—NPAR1WAY procedure, which incorporates a Kolmogorov-Smirnov two-sample test of frequency distributions. The assessment of life history stages was further examined by assessing the mean size of each species of fish caught in each of the five strata to see if there were any particular juvenile habitats. Significant trends across strata were assessed with linear and quadratic regressions of mean sizes for each species that occurred in three or more strata.

2.7.3 Results

Comparison Of Catch In Daytime And Night-Time Fish Trawls

The species presence or absence patterns were compared for 16 paired day and night fish trawls. Out of 210 species, 31 were caught only in day trawls and 71 were caught only in night trawls (with 108 in both). From the randomisation test, the number of night-only species was much higher than could be attributed to chance (66 species being the maximum observed for the randomisation distribution). This suggests that the observed frequency for the night-only category is a real rather than chance effect. The real number of day-only species was relatively low; lying within the lower tail of the distribution of frequencies produced by the randomisation test (31 being the 5th percentile of the randomisation distribution). This suggests that the observed frequency for the day-only category could be a chance effect.

Using the criterion that a species had to appear at 7 or more sites, the day-vs-night catchability was assessed for only 42 species. Seventeen species were more catchable at night (apogonids, scorpaenids and saurids) and only one was more catchable during the day (*Leiognathus bindus*; Figure 2.12). While the degree of catchability almost certainly differed between day and night for most species, it is interesting that the overall catch rate for species found at both times of day was in fact similar (day: 304.5 kg/h, SE 214.2; night: 263.1 kg/h, SE 222.7)

Comparison Of Fish And Prawn Trawl Catches

Fish catches (kg) from fish and prawn trawls from 122 sites were compared; 49 sites in 1992 and 73 in 1993. Out of a total of 340 fish species, 95 species were caught only by the fish trawler and 102 only by the prawn trawler (141 were common). From 1000 runs of the randomisation test, the actual number of species caught only by the fish trawl and only by the prawn trawl was greater than could be expected from the randomisation tests. This suggests that these results are real and not purely chance. The average catch rate for the fish trawl was 395.8 kg/h (SE = 141.3) and that of the prawn trawl 28.0 kg/h (SE = 1.7).

An analysis of variance of 150 fish species caught at seven or more sites showed that 58 species were caught in greater weight (average weight per shot) by the fish trawl (Appendix 2.A.1), 60 species by the prawn trawl (Appendix 2.A.2), and 32 species could not be differentiated statistically.

Differences in the catchability of fish could be attributed to gear type, to diel differences in behaviour, or to both. Examples of these differences are given in the next three paragraphs.

Five fish species (*Secutor insidiator*, *Uraspis uraspis*, *Atule mate*, *Sphyraena forsteri* and *Dussumieria elopsoides*) and two shark species (*Rhizoprionodon acutus* and *Carcharhinus dussumieri*) were caught only by the fish trawls (Appendix 2.A.1). These species showed no day or night preferences (Figure 2.12), so their catchability may depend on either differences in gear type or abundance. No sharks were caught by the prawn trawls.

The only species that was statistically more catchable by day in the fish trawl was *Leiognathus bindus*. It was also much more catchable by fish than by prawn trawls (mean difference in catch rate = 1.97±0.22; Appendix 2.A.1). This suggests that differences between the fish and prawn trawl catches were due to a combination of diel or behavioural responses and responses to different gear.

Of the 60 fish species that were caught in greater weight by the prawn trawl, about one third were caught only by the prawn trawl (Appendix 2.A.2). They were mainly apogonids, platycephalids, scorpaenids and flatfishes. Two of these species (*Apogon poecilopterus* and *Apogon brevicaudatus*) were caught only at night by both the fish and prawn trawl. The estimate for the difference in weight for *A. poecilopterus* between day and night catches (–0.706, Figure 2.12) is very similar to the estimate for the difference in weight between fish and prawn trawls (–0.71; Appendix 2.A.2) with similar confidence limits. Taken together these results suggest a strong nocturnal catchability, independent of the gear type.

Comparisons Of Length–Frequencies

Most of the fish taken by both types of trawl were small: in the fish trawl 86% were less than 30 cm (SL) and in the prawn trawl 92.5% were less than 30 cm (SL). The size–frequency distributions of 29 fish species were compared. Most species showed differences in the relative numbers caught by the two trawlers, but six species showed significant differences in the sizes caught (Table 2.10). The most notable was the commercial species *Diagramma pictum*; the mean size caught by the fish trawl was very much larger than that in the prawn trawl (Figure 2.13) and no large fish were taken by the prawn trawl.

Of the other commercial fish in the 122 sites sampled, 11 *Lutjanus sebae* (80–600 mm SL) and 922 *Lethrinus laticaudus* (170–390 mm SL) were caught by the fish trawl, whereas only one *L. sebae* (170 mm SL) and eight *L. laticaudus* (160–170 mm SL) were caught by the prawn trawl. The fish trawl also caught large fish—*Gnathanodon speciosus*, *Lutjanus malabaricus*, *Plectropomus maculatus* and *Epinephalus tauvina*—but no recreational or commercially important fish other than *Diagramma pictum* were caught by the prawn trawl.

The relative abundance of the fish species caught by each trawler varied greatly over the 30 min tow. Generally, more small benthic fish were retained by the prawn trawl, while more epibenthic and midwater fish were caught by the fish trawl. For example, in the case of the benthic fish *Scolopsis taeniopterus*—5274 individuals were caught by the prawn trawl compared to 1826 by the fish trawl—and the midwater fish *Selaroides leptolepis*—159 806 individuals were caught by the fish trawl and only 507 by the prawn trawl.

Table 2.10 A comparison of length–frequency distributions of fish caught by fish trawls and prawn trawls (n = 122 trawls) in the Far Northern Section of the Great Barrier Reef. Only species with more than 29 individuals in each net are listed. Size classes are at 10 mm intervals.

Species	Number of Fish	Mean Size (cm) * SD	Number of Fish	Mean Size (cm) * SD	*p* value	No of Size Classes
Apogon fasciatus	58	7.4±1.0	340	6.9±1.7	0.046	13
Canthigaster compressa	107	5.1±0.6	231	6.2±0.6	NS	5
Choerodon cephalotes	76	14.6±3.2	170	11.8±2.4	NS	17
Choerodon sp.2	126	11.3±1.4	79	10.1±1.7	NS	11
Diagramma pictum	81	34.6±18.5	79	10.2±1.6	0.0001	48
Fistularia petimba	295	32.2±3.3	86	31.9±4.4	NS	25
Gerres oyena	373	11.5±1.8	118	10.9±1.3	NS	10
Lagocephalus sceleratus	97	11.9±1.1	75	12.1±2.1	NS	11
Lethrinus genivittatus	4761	11.6±1.5	3198	11.2±1.5	NS	13
Nemipterus furcosus	1393	15.5±2.5	1809	13.6±3.4	NS	18
Nemipterus hexodon	64	14.2±3.5	72	12.1±4.1	NS	18
Nemipterus peronii	41	13.1±2.2	249	10.9±2.5	0.046	13
Paramonacanthus japonicus	49	8.3±1.4	397	8.2±1.2	NS	8
Pelates quadrifasciatus	507	10.2±0.6	445	10.2±0.7	NS	6
Pentapodus paradiseus	1083	13.9±1.3	871	12.9±2.0	NS	15
Pentaprion longimanus	488	8.1±1.0	76	6.8±1.4	NS	7
Plotosus lineatus	147	12.0±2.6	30	9.3±3.5	0.009	15
Priacanthus tayenus	79	16.2±3.1	167	15.1±3.3	NS	16
Pristotes jerdoni	558	7.8±1.1	379	8.2±0.9	NS	9
Saurida undosquamis	410	17.9±4.0	270	18.9±5.5	NS	30
Scolopsis taeniopterus	186	15.4±2.9	1448	9.9±2.4	0.046	17
Selariodes leptolepis	6244	12.3±1.5	134	12.5±1.9	0.014	13
Siganus canaliculatus	1367	12.5±1.2	170	11.6±1.8	NS	14
Sillago maculata	70	16.2±2.2	47	16.0±1.7	NS	9
Torquigener pallimaculatus	242	10.2±1.8	320	9.6±1.9	NS	13
Upeneus asymmetricus	225	11.9±1.0	685	11.8±1.2	NS	9
Upeneus luzonius	247	13.5±1.3	163	12.3±1.4	NS	10
Upeneus sundaicus	278	11.3±1.2	259	10.9±1.4	NS	10
Upeneus tragula	172	10.1±1.2	1056	9.9±1.1	NS	9

A total of 29067 fish of 249 species were measured during 1992 and 1993. Appendix 2.A.3 shows the mean size and number of 43 species of fish that were caught in each stratum. Species had to occur in at least 3 strata to be included. There were significant linear trends across the strata for 23 species and quadratic trends for 14 species. Most species with a significant linear trend tended to increase in size from inshore to offshore (such as *Choerodon cephalotes*) and those with a quadratic trend (such as *Nemipterus furcosus*) had their largest members in the mid shelf shoal regions (strata C and D). A full listing of mean sizes and SD is given in Appendix 2.B.1. No juveniles of any species were found other than those mentioned above.

2.7.4 Discussion

What Do Prawn Trawlers Catch?

About 141 species (41%) of the demersal fish community sampled at the 122 sites were caught by both the prawn trawl and the fish trawl. In addition, the prawn trawl caught a significant proportion (30%) of species that the fish trawl did not catch. They were generally flat-fish or very small fish that live on the seabed. Significantly, the prawn trawl rarely caught any of the important angling or commercial fish such as the lutjanids or lethrinids, and never caught coral trout or cod (which the fish trawler did catch), even though the trawls were done at the same sites. The only exception was the large and abundant (27–28% frequency of occurrence) painted sweetlip (*Diagramma pictum*), which was caught by both trawls. The remaining fish species (28%) were caught only by the fish trawler. Other than these species, the prawn trawler caught no discernible juvenile fish..

Diel differences in species composition, as shown by the 24 h trawling with the fish trawl, contributed significantly to the disparity between fish trawl and prawn trawl catches. For example, two species that contributed significantly to nocturnal catches by the fish trawl (*Apogon elliotti* and *Apistus carinatus*) were also more catchable in prawn trawl catches (which are made at night), and a species that was a significant component of fish trawl catches during the day (*Leiognathus bindus*), but not at night, was caught in much smaller numbers by the prawn trawl.

Diel differences in the catchability of fish probably reflect changes in their vertical distribution (Hobson 1972, 1974) or behaviour. Many of the leiognathids and some carangids move up into the water column at night and thus are not caught by a demersal prawn trawl. The leiognathids such as *L. bindus* are thought to follow the zooplankton as it spreads out through the water column at night (Blaber et al. 1990b). The carangid *Caranx bucculentus* feeds on benthic crustaceans and fish during the day (Brewer et al. 1989), but is not caught in bottom waters at night. The apogonids were more catchable at night (Figure 2.12), probably because they emerge at dusk from their daytime reef shelters to disperse and forage for food (Douglas 1982).

For many of the species of fish caught, differences in the relative numbers of large and small specimens caught in the fish and prawn trawls were marked. For example, the larger size classes of a species were generally caught in the fish trawl, while the more numerous, smaller size classes were caught in the prawn trawl. Large *D. pictum* were caught only in the fish trawl, while many juveniles were caught in the prawn trawl (Figure 2.13). Similarly, large sharks and rays were caught only in the fish trawl, while the small rays were caught only in the prawn trawl.

The two trawls also fished the water column differently. Pelagic fish such as scombrids and carangids and bentho-pelagic fish such as carangids and leiognathids were caught by the fish trawl, while many benthic apogonids, *Callionymus* and scorpaenids were caught by the prawn trawl.

The fish trawl probably catches a greater proportion of large and semipelagic fish because it (a) fishes higher off the seabed, (b) moves faster than the prawn trawl, (c) samples a greater volume of water above the seabed due to its large net opening and therefore catches fish further off the bottom, and (d) has long sweep wires, which may herd some fish (Ramm and Xiao 1995), which, after tiring, fall back into the net (Main and Sangster 1981; Andrew et al. 1991).

There are several reasons why the smaller fish are more often caught by the prawn trawl than the fish trawl. Firstly, the fish trawl, which is held off the seabed by the bobbins, does not fish as close to the seabed as does the prawn trawl, and some of the smaller fish, such as the scorpaenids and flat-fishes, may escape under the net (Godø and Walsh 1992). Secondly, the mesh of the fish net is much larger than that of the prawn trawl in the wings and body, and so some small fish could escape through it.

The response of benthic fish to trawl gear must also be considered. Studies of benthic fish in the north Atlantic found significant diel differences in their responses to trawl gear (Walsh and Hickey 1993): the fish's ordered orientation during the day breaks down at night, and some species react more slowly to the trawl footrope at night. In a multi-species fish community, such as those in the northern Great Barrier Reef, there are probably various behaviours and responses to trawl gear that complicate diel catchabilities.

The comparisons in this study were made with nets with specific types of ground gear. Any variations on this gear would probably result in different catch compositions. For instance, if a chain replaced the bobbin gear on the fish trawl, more of the small bottom fish might be caught. Similarly, if floats were used on the headrope of the prawn trawl, more of the bentho-pelagic fish might be caught.

The results of this study show that a prawn trawl catches only a subset of the fish population. This subset is composed of the smaller benthic species. The fish trawl catches show that a prawn trawl misses the larger more active species and also the more pelagic component. Thus the fish trawl catch of a prawn trawl is not an accurate representation of the fish fauna. This selectivity of the prawn trawl means that prawn trawling has a differential impact on species within the fish community, some are impacted and others are not. We might expect this to lead to a change in species composition in heavily trawled areas.

2.8 A quantitative description of the communities of prawn trawl catch (prawns & bycatch), fish and epi-benthic animals

2.8.1 Introduction

We studied the cross-shelf distribution of fish and benthic organisms on the Far Northern Section of the Great Barrier Reef (GBR). This project provided a unique opportunity to study the spatial distribution of fish and benthos among the relatively undisturbed coral reef communities and in adjacent heterogeneous cross-shelf habitats over an area of 3 429 900 ha (10 000 n.mile^2) of the northern Great Barrier Reef.

Two surveys (1992, 1993) were conducted to describe and compare the fauna and flora on or near the seabed inside and adjacent to the Cross-Shelf Closure (Figure 2.14a, b). The surveys involved sampling with the chartered fish trawler *Clipper Bird* and the QDPI prawn trawler *Gwendoline May*. The fish trawler sampled throughout daylight hours and the prawn trawler throughout the night. The fish trawler used a Frank and Bryce fish trawl net, a Church dredge and a video sled, and the prawn trawler used two Florida Flyer prawn trawl nets. The video sled was deployed from the port side of the fish trawler at the same time as the dredge was deployed from the starboard side. The duration of the tows was generally between 15 and 30 minutes depending on the device, at between two and three knots (1–1.5 m/s).

Before presenting the analysis of data from the prawn trawl, fish trawl and the benthic dredge, we have shown images from the video surveys to illustrate the nature of much of the seabed in the study area. This part of the reefs holds numerous reefs and shoals supporting myriad corals and sponges and other epibenthos. The regions between the reefs and the shoals are often bare or have small patchy areas of megabenthos (sponges, gorgonians and corals). This section of the report describes the spatial arrangement of these patches in shallow and in deep water. Video images of representative sessile megabenthos patches are presented (Figure 2.15).

The seabed and megabenthos visible from the video sled were assigned a code on a 0 to 9 scale, with bare sand as 1 (Figure 2.15a), 3 indicating algal beds (Figure 2.15c), 6 indicating epibenthic gardens with sponges (Figure 2.15f) and 9 indicating reef or live hard corals. The megabenthos was patchily distributed at several scales (Figure 2.16) and tended to have many associated organisms (e.g. fish, holothurians, crinoids, echinoids and asteroids). More megabenthos patches were found along the shallow transect than in the deep transect. These patches represent islands of high diversity surrounded by areas devoid of much structure. The megabenthos patches were often encountered on slightly raised portions of seabed, and the frequency of occurrence of such substrata was usually less than 5% of the video transects. The relative proportions of habitat types at the 1993 sites in the study area made from towed video sled observations (Figure 2.16c). Inshore (strata A and B), the habitat was mostly bio-turbated sand. Offshore, the sites were predominantly sandy with increasing complexity of habitat further offshore, in strata D and E. Sites on the shoals contained algal beds, shell beds and sparse to dense gardens of gorgonians, sponges and corals.

Sampling Design for Description of the Study Area --- YEAR 1

In the first year of the project, the distribution and abundance of the prawn, fish and epibenthic communities and the substratum types in the closure zone were described. The closed vs open comparisons and experimental trawling manipulations were undertaken in subsequent years and their design (wrt: spatial scales, replication, power, effect size etc) was based on the results of the descriptive study.

The design of the descriptive study took into account previous experience, from survey research in the Torres Strait and the Gulf of Carpentaria, in terms of spatial scales of patchiness and levels of variability in the prawns, fishes, epibenthos and sediment. This assisted decisions about the number and scales of replication in a hierarchical sampling design.

The sampling design for the descriptive study had a degree of regularity, necessary for the distributional information, and a random element, necessary for describing the scales of variablity in the study area and designing subsequent comparisons and manipulations. Initially, based on existing environmental and fisheries data relating to the study area and mapping undertaken using Landsat TM imagery, the study area was divided into four cross-shelf strata: (i) inshore lagoon, (ii) inshore reef/lagoon, (iii) mid-shelf reef/shoal matrix, and (iv) offshore lagoon. Latitudinally, the study area was divided into the closure zone and a similar area of the adjacent open zones, divided approximately equally north and south of the closure.

Stations were allocated at three spatial scales within inter-reefal habitats of the study area:

(1) The largest scale comprised 12 cells formed by the four cross-shelf strata and three areas: the closed zone and the adjacent open areas to the north and south. The cells sampled were approximately equal in area.

(2) The medium scale was based on that observed to be important in similar habitat elsewhere, namely that, on average, open seabed habitat changes little over distances of 5-10 km, but may be dissimilar at greater distances. Consequently, the medium scale, termed locations, was between 5 x 5 km and 10 x 10 km in area.

(3) The smallest scale was the sampling sites (or stations); these were selected at random from a 1 x 1 nautical mile grid within each location. Cost-benefit analyses of previous designs demonstrated that the optimum replication was 2 stations per location, which allowed estimation of the location and station level variance components but maximised replication where it was most beneficial (ie. the location level). Variation at scales smaller than ~1 n.mile should be integrated by the distance covered by the sampling devices used at each station.

Resources were available to sample a maximum of approximately 110 stations, which would correspond to about 5-10 km between stations. The procedure for actually selecting the sites to be sampled was as follows:

The study area was divided into a grid of size 1 x 1 n.mile and superimposed on a map showing the topography of the area, in particular the matrix of reef and shoals. Grid points that were deemed untrawlable (eg. on top of reefs) were removed and 2916 points remained. Within each of the 12 large scale cells, the grid points were clustered (objectively and without bias) into locations using k-means cluster analysis of their latitude and longitude coordinates. The k-means cluster analysis assigns cases to a specified number of groups by maximising between group variance relative to within group variance. The number of location groups in each cell was specified by dividing the number of grids in the cell by 13, to yield the chosen spatial scale for locations. Location groups varied in size between 9 and 21 grid points, but on average, contained 13.4 grid points. Then, location groups were chosen for sampling using a restricted randomisation technique where 25% of location groups were selected at random with the proviso that they could not be adjacent. Two sampling stations were selected at random from each of the selected locations, again with the proviso that stations could not be at adjacent grid points. Details of the allocation of sampling are shown in Table 2.11. This allocation would provide the most representative sampling of the study area, given the available resources and given the need to assess both large, medium and small-scale variation for the design of future research.

Table 2.11 Hierarchical sampling for Year 1 survey showing selection of sampling locations and locations. (a) number of 1x1 n.mile grid points and (b) number of location groups in each large scale cell, and (c) number of locations selected for sampling and (d) number of stations selected for sampling.

Zone		Stratum				
		Inshore Lagoon	Inshore reef & lagoon	Midshelf reef/shoal matrix	Offshore lagoon	TOTAL
North open	a	121	144	313	132	710
	b	9	11	23	10	53
	c	2	3	6	2	13
	d	4	6	12	4	26
Closed	a	431	317	796	265	1809
	b	32	23	59	20	134
	c	7	6	14	5	32
	d	14	12	28	10	64
South open	a	133	6	181	77	397
	b	10	1	13	6	30
	c	2	1	3	2	8
	d	4	2	6	4	16
TOTAL	a	685	467	1290	474	2916
	b	51	35	95	36	217
	c	11	10	23	9	53
	d	22	20	46	18	106

2.8.2 Methods

Collection of samples

In the analysis and description of the study area in this report we have combined the results of sampling in years 1 and 2 of the study. This was done to increase the quality and power of the patterns in biota distributions that we are presenting. The sampling for the year 2 open-vs-closed comparison differed from the year 1 survey in that only one station was sampled in each location (this was equivalent to restricted simple random sampling; it also included 5 strata as the midshelf reef/shoal matrix was divided in the second year of the project (see methods Chapter 3). It was possible to combine the data from both surveys because the location level variation was negligible and thus the year 1 data could be treated as if it was sampled with the same hierarchy as year 2 data, without compromising the interpretation of the analyses. For the purposes of analysis, the combined dataset is regarded as a random distribution of sampling sites within five cross-shelf strata.

The first sampling survey was during May 1992 and the second was during March 1993. The cross-shelf transect was partitioned into an inshore lagoon stratum (A), inshore reef-island stratum (B), two mid-shelf shoal-reef strata (C, D), and an offshore lagoon stratum (E). The mid-shelf shoal-reef zone was represented by two approximately equal (C, D) east–west strata to balance the size of areas sampled and to reflect the relative ecological importance of this habitat. Later in this report we combined Strata A and B into 'Inshore' and strata C, D and E into 'Offshore' regions. It was planned to sample 108 sites on each research cruise

(1992, 1993). Not all sites could be trawled due to weather and/or inappropriate sea bottom (Table 2.12 and Table 2.13). The spatial positions of sites for 1992, 1993 are shown in Figure 2.14 a,b.

Description of the prawn communities

Prawn samples were collected by the 18 m research trawler *Gwendoline May* towing two 4 fathom (8 m headrope) *Florida Flyer* nets over the stern in dual Otter trawl configuration. Details of the prawn nets are given in section 2.6.2

Each trawl tow was approximately 30 min long and covered 2.78 km (1.5 n.m), recorded as initial and final GPS position estimates with an inherent ±50 m error. Swept area was estimated as 28 836 m^2, assuming a 70% spread of each net (following Sparre et al. 1989). Prawns were sorted from both nets, bagged separately and snap frozen for transport back to the Northern Fisheries Centre, Cairns, for further analysis.

Samples from both the May–June 1992 (51 sites) and the March–May 1993 (79 sites) research cruises were combined and frequency of occurrence, abundance and biomass were calculated as numbers or weight per station for each stratum. Prawns were identified to species level with difficult identifications checked with Dr W. Dall, CSIRO Marine Laboratory, Cleveland. Biomass was calculated from individual carapace lengths converted to body weight according to the allometric equations derived from a subset of the catch that was both weighted and measured.

Prawn trawl bycatch samples

All samples were collected from the port-side net from the prawn trawler *Gwendoline May*. As the catch was spilled onto the sorting tray, a sample of up to 36 kg was removed from the catch; the rest was weighed in baskets to give a total catch weight. From the sample, prawns and valuable bycatch were removed and weighed. The remaining bycatch species were retained, labelled and placed into plastic bags for further analysis. All samples were frozen and transported to the laboratory. In the laboratory, the samples were thawed, identified to species (or groups where species were not identifiable), then each species was counted and weighed.

Fish trawl samples

The fish trawler *Clipper Bird*, which has an overall length of 25.9 m and an engine of 432 kW power, was used to deploy a Frank and Bryce fish trawl. Each tow was about 30 min long and covered about 3 km. Swept area was estimated at about 51000 m^2 with the net spread estimated at about 17 m The details of the trawl are given in Section 2.7.2.

If the catch weighed less than 100 kg, all of it was processed. For larger catches a subsample of the smaller individuals was taken. Total catches, or subsamples if catches were >100 kg, were frozen on board and analysed back in the laboratory. Every specimen larger than ~500 mm was identified to species, measured and weighed, and processed on board ship. Whenever a subsample was collected, the remaining catch was weighed and then discarded at sea. The numbers and weights of each species in the total catch were then calculated by multiplying up the catch from the subsample and adding all the larger fish not included in the subsample. Frequency of occurrence for each species was calculated as the number of sites at which that species was caught.

Table 2.12 Major activities carried out by stratum, during the initial survey cruise, in the Far Northern Section of the GBR (1992). The + sign indicates that the activity was carried out successfully

Station	Dredge	Fish trawl	Prawn trawl	Stratum	Station	Dredge	Fish trawl	Prawn trawl	Stratum
001	+	+	+	A	051	+	+	+	B
002	+	+	+	A	052	+	+	+	B
003	+	+	+	A	053	+	–	–	C
004	+	+	+	A	054	+	+	–	C
005	+	+	+	B	055	–	–	–	C
006	+	+	+	B	056	–	–	–	C
007	+	+	+	B	057	–	–	–	C
008	+	+	+	B	058	+	–	–	C
009	+	+	+	B	059	–	–	–	C
010	+	+	+	B	060	+	+	–	C
011	+	+	+	C	061	+	–	–	C
012	+	+	+	C	062	+	–	–	C
013	–	–	–	C	063	+	–	–	C
014	–	–	–	C	064	+	–	–	C
015	+	+	–	C	065	+	–	–	C
016	+	+	–	C	066	+	+	–	C
017	+	+	–	C	067	+	+	–	C
018	+	–	–	D	068	+	+	–	D
019	+	+	+	D	069	+	–	–	D
020	+	+	+	D	070	+	+	–	D
021	+	+	+	D	071	+	–	–	D
022	+	+	+	D	072	+	–	–	D
023	+	–	–	E	073	+	–	–	D
024	+	+	–	E	074	+	+	+	D
025	+	+	–	E	075	–	–	–	D
026	+	–	–	E	076	–	–	–	D
027	+	+	+	A	077	–	–	–	D
028	+	+	+	A	078	–	–	–	D
029	+	+	+	A	079	–	–	–	D
030	+	+	+	A	080	–	–	–	D
031	+	+	+	A	081	+	+	–	E
032	+	+	+	A	082	+	+	–	E
033	+	+	+	A	083	–	–	–	E
034	+	+	+	A	084	+	+	–	E
035	+	+	+	A	085	–	–	–	E
036	+	+	+	A	086	+	+	–	E
037	+	+	+	A	087	+	–	–	E
038	+	+	+	A	088	+	–	–	E
039	+	+	+	A	089	+	+	–	E
040	+	+	+	A	090	+	–	–	E
041	+	+	+	B	091	+	+	+	A
042	+	+	+	B	092	+	+	+	A
043	+	+	+	B	093	+	+	+	A
044	+	+	+	B	094	+	+	+	A
045	+	+	+	B	095	+	+	+	B
046	+	+	+	B	096	+	+	+	B
047	+	+	+	B	097	+	+	–	C
048	+	+	+	B	098	+	+	–	C
049	+	+	+	B	099	+	–	–	D
050	+	+	+	B	100	+	–	–	D

Table 2.13 Major activities carried out by stratum, during the Open versus Closed survey (1993), in the Far Northern Section of the GBR. The + sign indicates that the activity was carried out successfully

Station	Dredge	Fish trawl	Prawn trawl	Stratum	Station	Dredge	Fish trawl	Prawn trawl	Stratum
001	+	+	–	C	051	+	+	+	B
002	+	+	–	C	052	+	+	+	C
003	+	+	+	C	053	+	+	+	C
004	+	+	+	C	054	+	+	+	C
005	+	–	–	C	055	+	–	–	C
006	+	+	+	D	056	+	+	+	C
007	+	–	–	D	057	+	+	+	D
008	+	+	–	D	058	+	+	+	D
009	+	+	–	D	059	+	+	+	D
010	+	+	+	D	060	+	–	+	D
011	+	+	–	E	061	+	–	–	E
012	+	+	–	E	062	+	+	+	E
013	+	–	–	E	063	+	–	–	E
014	+	–	–	E	064	+	–	–	E
015	+	–	–	E	065	+	+	+	E
016	+	+	+	E	066	+	+	+	E
017	+	+	+	E	067	+	+	+	D
018	+	+	+	E	068	+	+	+	D
019	+	+	+	E	069	+	–	+	D
020	+	–	–	E	070	+	–	+	C
021	+	+	+	E	071	+	+	+	D
022	+	+	+	E	072	+	+	+	C
023	+	+	+	E	073	+	–	–	C
024	+	+	+	E	074	+	+	+	C
025	+	–	–	E	075	+	+	+	C
026	+	–	–	E	076	+	+	+	B
027	+	+	+	D	077	+	+	+	B
028	+	+	+	D	078	+	+	+	B
029	+	+	+	D	079	+	+	+	B
030	+	–	–	C	080	+	+	+	B
031	+	+	+	C	081	+	+	+	A
032	+	+	+	D	082	+	+	+	A
033	+	+	+	C	083	+	+	+	A
034	+	+	+	C	084	+	+	+	A
035	+	+	+	B	085	+	+	+	A
036	+	+	+	B	086	+	+	+	A
037	+	+	+	B	087	+	+	+	A
038	+	+	+	B	088	+	+	+	A
039	+	+	+	B	089	+	+	+	A
040	+	+	+	C	090	+	+	+	A
041	+	+	+	C	091	+	+	+	A
042	+	+	+	B	092	+	+	+	A
043	+	+	+	B	093	+	+	+	A
044	+	+	+	B	094	+	+	+	A
045	+	+	+	B	095	+	+	+	A
046	+	+	+	B	096	+	+	+	A
047	+	+	+	B	097	+	+	+	A
048	+	+	+	B	098	+	+	+	A
049	+	+	+	B	099	+	+	+	A
050	+	+	+	B	100	+	+	+	A

Dredge samples

The dredge is a 3.0 m wide by 1.2 m high beam trawl or "Church Dredge" rigged with a 30 mm mesh net bag. Each tow with the dredge lasted up to 15 minutes at 6 km h^{-1} (3.0 knots) from the starboard boom of the *Clipper Bird*. The dredge sampled the top of the substratum, depending on the nature of the substratum, as well as associated benthos. One tow was made at each station.

The dredge samples were roughly sorted on board. The large sessile megabenthos, mainly sponges, corals and gorgonians, were sorted and counted immediately after collection, and the fresh weight was recorded to the nearest 100 g. A small piece of each was retained for identification. A subsample was collected for the remaining catch and the amount remaining was weighed in baskets and discarded. A taxonomist from the Queensland Museum identified the subsamples to species or putative taxon, and then counted and weighed them to the nearest 1 g.

Data preparation

The data were standardised to weight and numbers for each species or taxonomic group. Tows of short duration were rejected and the data were not used. For the bycatch data, prawn trawls of less than 11 minutes were rejected; fish trawls of less than 15 minutes were rejected; and benthic dredge hauls of less than 7 minutes were rejected.

In cases where a subsample was collected, the total number and weight of each species or taxonomic group in the subsample were multiplied by a catch-grossing factor (CGF) based on the ratio of subsample to total weight recorded: CGF = 1 + (Discarded weight / Subsample weight).

The weight data for each species was transformed as $\log_{10}$(weight + 0.5*minwt) where minwt is the smallest non-zero weight for that species. A similar transformation was used to transform the numbers data. This choice of constant for the log-transformation has the effect of keeping the zeros close to the remainder of the non-zero data after transformation, whereas no fixed constant (such as 1) can be guaranteed to do this for all species. For example, suppose one taxon was found in quantities ranging from 100 g to 1000 g. If a value of 1 were added to all weights, the locations where that taxon was absent would be represented as 0 on the log-transformed scale while all the other weights would range from 2 to 3. In this case, adding a value of 1 would artificially inflate the variance of the log-transformed data, producing a variance twice or three times as large as the variance from the method used here.

Spatial analysis of the species composition

The spatial variation of the biological communities caught by all three devices (prawn trawl, fish trawl and benthic dredge) was examined using principal component analysis (PCA) on the log-transformed weight data. The aim was first to see whether differences among communities in the five strata could be detected without spatial structure being imposed. Multivariate analysis of variance was later used to impose this structure. We used PCA primarily as a dimension reduction technique, rather than an ordination method. It also proved to be a better tool than MDS for visually separating the strata.

The principal component (PC) scores for stations were plotted, with different symbols for the different strata. The eigenvector coefficients for each species were also plotted, with labels for outlying species. There is a direct link between these two plots that is exploited by the biplot technique (Digby and Kempton, 1984). In our study there were many stations and many species, so a biplot (of species by stations) would not be effective visually. However, it is useful to explore the relationship between PC scores for the stations and eigenvector coefficients for the species. The principle behind this is that a species which appears in, for example, the top right of the eigenvector plot will be most abundant in stations that appear in the top right of the station PC scores plot. Similarly, species that appear in the bottom left of the eigenvector plot will be most abundant in stations that appear in the bottom left of the station PC scores plot.

We used multivariate analysis of variance (implemented in the SAS GLM procedure) to evaluate formally whether the species composition differed among strata: essentially a one-way analysis with stratum (5 levels) as the factor. For this analysis, the data set consisted of a station by species matrix of log-transformed weight data, together with a column containing the stratum label for each station. We used the Wilks' lambda test statistic for the hypothesis test, but, in practice, the *p*-values were found to be similar for all of the commonly used statistics. Data were $\log_{10}$ transformed in the same way as for principal component analysis.

We considered it important to check the validity of the *p*-value, particularly given the large number of zeros in the data. To assess the bias in the *p*-value, we produced a permutation distribution of the Wilks' lambda statistic (see, for example, Sokal and Rohlf 1969 for an introduction to this approach). The distribution is based on the value of the statistic obtained for a large number of randomly generated permutations of the data set, each permutation data set having been generated by re-ordering the stratum labels in a random manner but preserving the species–weight records for each station. We carried out multivariate analysis of variance on each permuted data set and recorded the value of the Wilks' lambda statistic. When 5000 such permutations had been carried out, we compared the cumulative distribution of the Wilks' lambda statistic with the theoretical cumulative distribution corresponding to the F-distribution with the degrees of freedom associated with the stratum effect in the multivariate analysis of variance. There is a very close correspondence between the two cumulative distributions. When the permutation distribution was superimposed on the theoretical distribution, it was almost impossible to separate them visually. Similar results were obtained for the fish, bycatch and benthos data sets. We have concluded that the *p*-value produced by the multivariate analysis of variance is unbiased for these data sets, and assume that it is equally appropriate for the multivariate analyses reported in later chapters.

We extended the use of multivariate analysis of variance to examine whether any of the five strata could be amalgamated because their communities are not very different. Pairs or triples of adjacent strata were formed into groups, and a model was fitted involving the terms group and stratum-within-group. For example, the five strata were put into four groups by amalgamating strata A and B. In univariate analysis of variance this would give one degree of freedom for within-group variation and three degrees of freedom for between-group variation. In multivariate analysis of variance, there are more degrees of freedom than this but the pattern is the same: three times as many numerator degrees of freedom for between-group variation as for within-group variation.

Species richness

The species richness of the communities was examined in two ways: per trawl and per region. The methods offer complementary information about diversity.

The per trawl measures consisted of the total number of species caught and the total biomass per trawl. Both measures were used on various groups; a measure was chosen specifically for each data set. The total number of species caught per trawl is presented graphically and is plotted against longitude, with symbols to identify the stratum. The difference in numbers and weight ($\log_{10}$ transformed) per trawl across strata were analysed with a one-way ANOVA.

Species richness per region was assessed in two ways—species area curves (except for prawns) and a matrix showing number of species in each stratum and in common between pairs of strata. In addition to this, results were obtained for the "inshore" and "offshore" regions. Species area curves were generated for the Inshore (Strata A and B) and Offshore (Strata C, D and E) groups by incrementing the number of new species caught with each additional tow after the first one. The matrix was used to show the number of species in common between strata or between Inshore and Offshore. This exercise was repeated for fish, crustaceans and molluscs, and other classes for the benthos.

There were an uneven number of sites among the five strata for between Inshore and Offshore. A random subset of the data from *n* stations was selected, n being the number of stations in the stratum with fewest stations – usually stratum E. For that stratum, no subsetting was required. Table 2.14 shows the number of sites per stratum for each sampling device.

Table 2.14 The number of sites in each stratum represented in the fish trawl, the prawn trawl or the benthic dredge

Device	Stratum A	Stratum B	Stratum C	Stratum D	Stratum E
Fish trawl	42	40	28	23	19
Prawn trawl	40	39	17	17	9
Dredge	41	40	31	24	21

Comprehensive species statistics for each sampling device

A full listing of all species (or groups) from the two survey cruises in 1992 and 1993 is presented in Appendices 2.B.1 and 2.B.2 (bycatch), 2.C.1 and 2.C.2 (fish) and 2.D.1 (benthos) giving the mean catch rate and standard deviation. For fish, the listing included the mean size, standard deviation and number of specimens measured. Catch rate was standardised to weight caught per hour (g h^{-1}).

2.8.3 Results

2.8.3.1 Results for prawns

Twenty two species of Penaeidea were collected from the Cross-Shelf Closure and adjacent cross-shelf areas, although five species were rare (consisting of less than 20 specimens collected). The mean abundance and biomass values were very low for all species, less than 16 animals per hectare when averaged over all sampling sites. Low numbers are in part explained by the concentration of any given species within a smaller subset of the sampling sites. This is also reflected by the standard deviation being greater than the mean for all species (which can also indicate highly skewed distributions, Zar 1974).

Spatial analysis of prawn communities

A total of 14 species were used in the principal component analysis. An ordination of sites (n=126) based on a plot of the scores of the first principal component (PC-1) against the second principal component (PC-2; Figure 2.17) clearly demonstrates differences in the species composition of sites from different strata. The first, second and third principal components explained 33.5%, 31.1% and 9.5% of the variation respectively. The curvature in the trend across strata is due to some species having peak abundance in strata B, C or D while others peak in strata A or E. There is considerable overlap of the prawn communities from sites in strata A and B—inshore (brown triangles and red squares respectively) and from strata D and E – offshore (blue circles and purple triangles) suggesting these pairs of sites have relatively similar communities compared with the difference between communities inshore and offshore. The prawn community on the shoals in stratum C (green diamonds) separates out from all the others while the prawns from the deeper gutters in stratum C (green stars) seem to be comparable to those in strata D and E and some from stratum A.

The first principal component plotted spatially (Figure 2.18) shows three distinct groupings with two groups inshore (yellow squares and red triangles) and the other group (blue circles) offshore. Within the two inshore strata there is evidence of latitudinal separation between the squares and triangles clearly separating these communities into northern and southern communities. The second principal component plotted spatially (Figure 2.19) shows similarities between sites offshore and those in the northern parts of strata A and B (yellow squares) and clearly separates them from the other sites (blue circles).

Principal component analysis was also used to show the relationship between prawn species based on their abundance at sample sites. The eigenvectors from the first and second principal components are plotted (Figure 2.20). Species that group together on this plot have similar patterns of abundance within the study area. The central group of closely clustered points—near (0, 0)—represent the group of species that have a low biomass across all strata (*Penaeus semisulcatus, Metapenaeopsis wellsi, M. crassissima, Trachypenaeus anchoralis*) (Table 2.15)

Table 2.15 Mean weight (g) of Penaeid prawn species collected by the prawn trawler from each stratum in the study site of the far northern Great Barrier Reef during 1992-1993.

	Stratum				
Species	**A**	**B**	**C**	**D**	**E**
Metapenaeopsis crassissima	0.00	0.07	0.00	0.02	5.90
Metapenaeopsis lamellata	0.00	0.00	1.61	2.14	2.44
Metapenaeopsis mogiensis	0.00	0.00	16.53	31.22	22.81
Metapenaeopsis palmensis	1.66	7.64	9.87	0.35	0.31
Metapenaeopsis rosea	8.41	15.42	135.77	25.18	6.48
Metapenaeopsis wellsi	0.00	0.00	0.00	0.17	3.79
Metapenaeus endeavouri	280.29	484.11	209.87	39.65	2.43
Penaeus esculentus	231.84	402.83	103.73	0.00	0.00
Penaeus latisulcatus	126.39	5.63	11.31	4.11	0.00
Penaeus longistylus	39.35	105.94	196.63	209.94	58.22
Penaeus semisulcatus	2.76	1.12	0.00	0.00	0.00
Trachypenaeus anchoralis	1.30	0.90	0.06	0.43	0.00
Trachypenaeus curvirostris	0.00	0.00	17.42	49.22	29.71
Trachypenaeus granulosus	8.69	20.88	36.30	0.64	1.17
Number of trawl tows	**49**	**39**	**17**	**17**	**9**

Species not in or near this central group have a more distinctive distribution pattern throughout the study area. *Penaeus esculentus*, *P. latisulcatus*, and *Metapenaeus endeavouri* were concentrated in the inshore lagoon to inshore reefs and islands (Strata A and B). *Trachypenaeus granulosus* and *Metapenaeopsis palmensis* were concentrated in Strata B and C. *Penaeus longistylus* was concentrated in the reef-shoal zone (Strata C and D). *Metapenaeopsis rosea* was concentrated in Stratum C. *Metapenaeopsis lamellata*, *Metapenaeopsis mogiensis* and *Trachypenaeus curvirostris* were concentrated offshore (Strata D and E). Table 2.15 shows the mean biomass per species in each stratum.

The results of the MANOVA for the station by species matrix were highly significant (p = 0.0001, Wilks' Lambda = 3.4919), which confirmed the between-stratum differences seen in the unstructured analysis.

No combination of strata was found with a highly significant between group variation and a non-significant within group variation (Table 2.16).

Table 2.16 Results of the MANOVA on prawn species to assess the amount of variation between groups and within groups. Adjacent strata have been combined into groups of 2 or 3 strata.

Group	F-Prob	No. of Groups	F-ratio	Numerator df	Denominator df
A/B/C/D/E	$< 10^{-10}$	5	10.4529	56	422
AB/C/D/E between	$< 10^{-9}$	4	11.7318	42	321
AB/C/D/E within	$< 10^{-10}$	4	7.399	14	108
A/BC/D/E between	$< 10^{-10}$	4	11.8632	42	321
A/BC/D/E within	$< 10^{-10}$	4	7.8328	14	108
A/B/CD/E between	$< 10^{-10}$	4	12.8146	42	321
A/B/CD/E within	$< 10^{-9}$	4	7.1608	14	108
A/B/C/DE between	$< 10^{-10}$	4	11.2791	42	321
A/B/C/DE within	$< 10^{-10}$	4	8.3343	14	108
AB/CD/E between	$< 10^{-10}$	3	16.3217	28	216
AB/CD/E within	$< 10^{-10}$	3	7.0003	28	216
AB/C/DE between	$< 10^{-10}$	3	13.6875	28	216
AB/C/DE within	$< 10^{-10}$	3	7.7694	28	216
A/BC/DE between	$< 10^{-10}$	3	13.5485	28	216
A/BC/DE within	$< 10^{-10}$	3	7.9008	28	216
A/BCD/E between	$< 10^{-10}$	3	11.3488	28	216
A/BCD/E within	$< 10^{-10}$	3	11.2402	28	216
ABC/DE between	$< 10^{-10}$	2	23.2391	14	108
ABC/DE within	$< 10^{-10}$	2	7.5903	42	321
AB/CDE between	$< 10^{-10}$	2	26.7041	14	108
AB/CDE within	$< 10^{-10}$	2	7.8588	42	321

Cross shelf patterns of occurrence of prawns.

Species frequency of occurrence (Table 2.17), mean abundance (Table 2.18) and, mean biomass (Table 2.15) are presented for each stratum for the fourteen most abundant species. There was a pronounced gradient in some species distribution from inshore to offshore with two loose groupings of inshore and offshore species. The inshore species were mostly the large-bodied commercial prawn species and the offshore species were more numerous small-bodied animals. The Red Spot King prawn (*Penaeus longistylus*) was the exception; this large-bodied, commercially important species was concentrated in the reef-shoal region (Strata C and D) rather than inshore.

Table 2.17 Percent occurrence of Penaeid prawn species collected by the prawn trawler from each stratum in the study site of the far northern Great Barrier Reef during 1992-1993.

	Stratum				
Species	**A**	**B**	**C**	**D**	**E**
Metapenaeopsis crassissima	.	3	.	5	40
Metapenaeopsis lamellata	.	.	41	47	60
Metapenaeopsis mogiensis	.	.	47	68	100
Metapenaeopsis palmensis	45	50	59	16	20
Metapenaeopsis rosea	33	43	88	79	40
Metapenaeopsis wellsi	.	.	.	11	40
Metapenaeus endeavouri	93	100	76	26	10
Penaeus esculentus	93	100	71	.	.
Penaeus latisulcatus	83	38	29	16	.
Penaeus longistylus	68	83	88	95	60
Penaeus semisulcatus	23	10	.	.	.
Trachypenaeus anchoralis	28	30	6	11	.
Trachypenaeus curvirostris	.	.	47	63	50
Trachypenaeus granulosus	43	60	65	16	30
Number of trawl tows	**49**	**39**	**17**	**17**	**9**

Table 2.18 Mean number of Penaeid prawn species collected by the prawn trawler from each stratum in the study site of the far northern Great Barrier Reef during 1992-1993.

	Stratum				
Species	**A**	**B**	**C**	**D**	**E**
Metapenaeopsis crassissima	0	<1	0	<1	2
Metapenaeopsis lamellata	0	0	<1	1	1
Metapenaeopsis mogiensis	0	0	7	13	10
Metapenaeopsis palmensis	1	6	4	<1	<1
Metapenaeopsis rosea	2	6	31	7	2
Metapenaeopsis wellsi	0	0	0	<1	1
Metapenaeus endeavouri	20	24	9	1	0
Penaeus esculentus	9	11	2	0	0
Penaeus latisulcatus	5	<1	<1	<1	0
Penaeus longistylus	2	4	10	9	2
Penaeus semisulcatus	<1	<1	0	0	0
Trachypenaeus anchoralis	1	1	<1	<1	0
Trachypenaeus curvirostris	0	0	7	20	8
Trachypenaeus granulosus	4	13	13	<1	1
Number of trawl tows	**49**	**39**	**17**	**17**	**9**

2.8.3.2 Results for bycatch

General description of the bycatch

A total of 1.88 t and 50 075 individual items of discards were collected from 122 tows made during the surveys in the Far Northern Section of the Great Barrier Reef over the two years of 1992 and 1993. Of this, fish were the primary component, 69% by weight and 71% by number; crustaceans were the second largest component, 8.5% and 16% respectively. A total of 356 species and groups were identified from the 122 tows. The species caught during the two surveys are presented along with mean catch rate, mean size for fish and the standard deviations in Appendix 2.B.1. Of the nine elasmobranch species caught, two were sharks and the rest were rays. Twelve fish species could be identified only to family level and ten fish only to genus level.

Most of the invertebrates (Appendix 2.B.2) were identified to class level. Crustaceans were identified to species level. All sponges were combined as one group since there were numerous undescribed species and many were fragmented. There were 12 Cnidarian groups, 63 crustacean groups, 19 molluscan groups, one byozoan group, 10 Echinoderm groups and one ascidian group

Spatial analysis of bycatch composition

A total of 118 species were used in the principal component analysis. An ordination of sites (n=122) based on a plot of the scores of the first principal component (PC-1) against the second principal component (PC-2; Figure 2.21) clearly demonstrates differences in the species composition of sites from different strata. There is considerable overlap of the bycatch communities from sites in strata A and B—inshore (red squares and left pointing brown triangles respectively) suggesting similarities of the communities among these sites. Although there is overlap of the bycatch communities of strata D and E (blue circles and purple right pointing triangles)—offshore the overlap is not as strong, which suggests that the communities are different between these strata. The fish community in stratum C (green diamonds and stars) shows some similarity with the inshore and offshore communities, but is clearly separated from them. The sites in the deeper water (diamonds) are mostly distinct from the other strata with some overlap of communities inshore. Communities of bycatch at sites on the shoals (stars) generally have closer affinity with those in offshore waters (Figure 2.21).

The first principal component explained 19.5% of the variation and, plotted spatially (Figure 2.22), demonstrates a marked difference in bycatch species composition between inshore sites (red triangles, scores > 1.0) and offshore sites (blue circles, scores <-3.0). The symbols are interspersed and gradually shift from high-value scores inshore to low-value scores offshore, which reflects changes in community composition from the coast to the outer barrier reef. There are seven sites in stratum A that have scores similar to those at sites further offshore in stratum C (yellow squares).

The second principal component explained 7.6% of the variation. This component, plotted spatially (Figure 2.23) separates the sites, particularly those in the central shoals from those inshore and offshore. The trend is for lower scores (blue circles, scores < 0) in strata B, C and D and high scores (squares) inshore and offshore. Effectively, the second principal component, in conjunction with the first principal component separates Stratum D from A and Stratum D from E.

The principal component analysis was also used to show the relationship between bycatch species based on their biomass at sample sites. The eigenvectors from the first and second principal components are plotted in Figure 2.24. Species that group together have similar patterns of distribution within the study site. The central group of closely clustered points—near (0, 0)—represent a large group of species that are relatively evenly distributed across all strata. Species not in or near this central group have more distinctive patterns of abundance throughout the study area. Those species on the left (ie *Apogon fasciatus, Scolopsis taeniopterus*) are more abundant inshore and those on the right (ie *Pristotis jerdoni*, Crinoids) are more abundant offshore (see Table 2.19).

Table 2.19 Mean weight(kg) of bycatch species caught by the prawn trawler from each stratum in the study site of the Far Northern Section of the Great Barrier Reef.

	Stratum					
Species/group	**A**	**B**	**C**	**D**	**E**	**Total No**
Teleostii						
Apogon ellioti	0.12	0.18	0.1	0	0	909
Apogon fasciatus	0.08	0.07	0.01	0	0	719
Nemipterus furcosus	2.11	3.05	2.84	0.71	0.39	3503
Pristotis jerdoni	0.01	0	0.04	0.18	0.59	508
Scolopsis taeniopterus	0.96	1.08	0.45	0	0	2712
Sorsogona tuberculata	0.04	0.1	0.19	0.08	0.04	672
Porifera						
Sponges mixed species	4.88	0.73	2.84	0.02	0.07	119
Crustaceans						
Thenus maculata	0.02	0.01	0.37	0.49	0.13	100
Molluscs						
Amussiidae	0.51	0.76	0.04	0	0	4501
Echinoderms						
Crinoidea	0	0.01	0.03	0.11	0.19	276
Holothurioidea	0.02	0.01	0.07	0.41	1.56	37

Tables of the mean biomass of common species, (Table 2.19, Appendix 2.B.4) demonstrate a range of distribution patterns of species across the coastal shelf (strata). The most common pattern involves those species that increase in biomass from stratum A, reach a maximum in stratum B and then decrease to a minimum in stratum E. Examples of those species are fish: *Nemipterus furcosus*, *Scolopsis taeniopterus*, *Apogon elliotti* and the crab: *Portunus tenuipes*. Coastal species (fish: *Paramonacantis choirocephalus*, *Upeneus tragula*; scallops: Amusiidae) have a greater biomass in stratum A than in any of the other strata and rapidly decrease in biomass further offshore. Crinoids are more common in offshore strata. Sponges and the fish *Lethrinus genivittatus* are least common in the midshelf strata. Several species complement each other in their biomass distribution across the strata—*Apogon ellioti* has a higher biomass inshore than *Apogon moluccensis* which has a higher biomass offshore—and *Lethrinus genivittatus* has a high biomass inshore and offshore, but has low biomass in strata C and D, whereas *Pentapodus paradiseus* has high biomass in strata C and D, but low biomass in strata A, B and E.

The results of the MANOVA for the station by species matrix, with 97 species present at 15 or more sites for 122 sites, were highly significant (p = 0.0001, Wilks' Lambda = 3.4919), which confirmed the between-stratum differences seen in the unstructured analysis.

The results of the MANOVA on bycatch species groups indicate that strata B and C appear to be most similar, suggesting four distinct cross shelf strata (Table 2.20).

Table 2.20 Results of the MANOVA on bycatch species/taxa to assess the amount of variation between groups and within groups. Adjacent strata have been combined into groups of 2 or 3 strata. The optimum combination is highlighted in bold text.

Group	F-Prob	No. of Groups	F-ratio	Numerator df	Denominator df
AB/C/D/E between	$< 10^{-8}$	4	3.8863	291	64
AB/C/D/E within	$< 10^{-3}$	4	3.5333	97	21
A/BC/D/E between	**$< 10^{-9}$**	**4**	**4.1372**	**291**	**64**
A/BC/D/E within	**0.059**	**4**	**1.8207**	**97**	**21**
A/B/CD/E between	$< 10^{-9}$	4	4.2647	291	64
A/B/CD/E within	$< 10^{-3}$	4	4.474	97	21
A/B/C/DE between	$< 10^{-8}$	4	3.7831	291	64
A/B/C/DE within	$< 10^{-2}$	4	2.6651	97	21
AB/CD/E between	$< 10^{-2}$	3	5.4615	194	42
AB/CD/E within	$< 10^{-5}$	3	3.3184	194	42
AB/C/DE between	$< 10^{-7}$	3	4.6025	194	42
AB/C/DE within	$< 10^{-4}$	3	3.0271	194	42
A/BC/DE between	$< 10^{-8}$	3	5.1524	194	42
A/BC/DE within	$< 10^{-2}$	3	2.174	194	42
A/BCD/E between	$< 10^{-8}$	3	5.5404	194	42
A/BCD/E within	$< 10^{-5}$	3	3.5704	194	42
ABC/DE between	$< 10^{-7}$	2	10.6298	97	21
ABC/DE within	$< 10^{-5}$	2	2.6492	291	64
AB/CDE between	$< 10^{-7}$	2	10.4506	97	21
AB/CDE within	$< 10^{-7}$	2	3.2281	291	64

Cross shelf patterns of occurrence of bycatch

The cross-shelf region was divided into five strata based on sediment type. The frequency of occurrence of the bycatch in each of the strata was recorded where the total number of each species was at least 100 (Appendix 3.B.3). Several fish species were only found inshore (i.e. *Pelates quadrilineatus*, *Nemipterus hexodon*, *Nemipterus peronii*) while others were distinctly offshore species (i.e. *Apogon nigrocincta*, *Apogon moluccensis*). Of these, 41% of the 49 fish species were found across all strata, 51% were mostly inshore, 6% were offshore and the remainder in the mid-shelf. 50% of the 6 crustaceans were found inshore and the other half offshore. The sponges, as a group, were found across all strata. The mean number of species that were caught at each station in each of the five strata are shown in Appendix 2.B.5.

Table 2.21 shows the range of numbers of species that were found in each of the five strata and in the groups for inshore and offshore strata. These are shown in bold type down the diagonal. For example, there were between 93 and 109 fish species in subsets of 9 sites in stratum A. The range of species numbers (in every case except stratum E and the offshore stratum) comes from the 20 random subsets of 9 sites that were taken in each of the other strata in order to compensate for the unequal number of sites sampled in each stratum. Table 2.21 also shows how many species were in common between pairs of strata. For example, there were between 65 and 77 fish species in common between stratum A and stratum B.

The species in the bycatch data sets have been examined in several groups: fish species, crustaceans and, finally, all bycatch. The first three groups were sorted to species level for almost all animals, whereas the remainder contains a moderate number of animals that were identified to class level.

The number of fish species declines from inshore (stratum A) to offshore (stratum E), while the overlap in species among strata A, B and C is fairly high. The overlap in species between A and B represents slightly more than 50% of the number of species found in A and B collectively. There are fewer species in common among strata that are further separated: for example, only 26 to 33 species are in common between strata A and E. The overlap in this case represents about 20% of the number of species found in A and E collectively.

Once strata A and B have been aggregated into inshore and C, D and E into offshore, the two regions differ very little in richness of fish species, and the overlap contains just under 50% of the 230 or so species represented in the whole study area (with stratum A represented by subsets).

The patterns observed for fish species were broadly repeated for crustaceans, for which there were about 50 species in the whole study area (from subsets of sites). Similarly for bycatch as a whole, for which there were about 300 species or classes in the whole study area (again, from subsets of sites).

Table 2.21 Species richness for bycatch caught by the prawn trawler in each stratum in the study area of the far northern Great Barrier Reef during 1992-1993. The bold text is the number of items in each stratum.

Stratum	**A**	**B**	**C**	**D**	**E**	**Inshore**	**Offshore**
Fish species							
A	**93–109**	65–77	51–72	35–51	26–33	**149–160**	92–101
B		**82–97**	52–67	36–48	24–30		**166**
C			**82–102**	42–58	32–42		
D				**64–75**	33–41		
E					**75**		
Crustaceans							
A	**15–25**	11–17	8–16	5–8	5–7	**35–44**	20–23
B		**14–24**	10–17	5–8	5–8		**34**
C			**15–22**	6–10	6–8		
D				**9–16**	6–9		
E					**11**		
All bycatch							
A	**131–151**	90–106	75–102	47–68	43–52	**219–240**	139–148
B		**119–140**	73–96	54–67	41–50		**231**
C			**123–141**	67–83	54–69		
D				**91–112**	55–68		
E					**108**		
Total number of tows	**9 of 40**	**9 of 39**	**9 of 17**	**9 of 17**	**9**	**43 of 79**	**43**

Species richness

The species richness (biomass per trawl, no. of species per trawl) for bycatch in each stratum was estimated for all species combined and for three major taxonomic groups: fish, crustaceans and molluscs. The latter is not presented graphically as there were too few species per station per stratum.

The plots of the number of species and the ($\log_{10}$) biomass per station show a similar trend across the strata. The number of species of fish per station decreases from the inshore stratum (A) to the offshore stratum E; (Figure 2.25) This trend is similar for the crustaceans (Figure 2.26) but not as strong. The biomass of fish per station increases slightly across strata A and B, and then decreases from stratum C to E (Figure 2.27). For the fish and crustaceans (Figure 2.28) there is a marked decline in biomass to stratum E. There is a high degree of variation in the number and weight of aggregated bycatch species between sites within each stratum. Despite these variations, there are significant correlations between number of species or biomass decreasing across the strata (i.e. for fish $R = 0.54$, crustacea $R = 0.62$, molluscs $R = 0.43$ and, for all species combined R = 0.39 and $P = < 0.001$).

Analysis of variance also shows significant decreases of total biomass and numbers of all species in any trawl across the strata from inshore to offshore. This trend remains apparent for the three main groups, fish, crustaceans and molluscs (Table 2.22).

Table 2.22 Results of a one-way ANOVA of bycatch number and biomass ($\log_{10}$kg/tow) over five strata from inshore to offshore across the continental shelf of the Far Northern Section of the Great Barrier Reef Marine Park.

Group			Stratum				
		P	A	B	C	D	E
Fish	Number	0.0001	42	38	31	21	20
	Log Weight	0.0001	1.06	1.12	1.06	0.92	0.68
Crustaceans	Number	0.0001	7	7	6	4	3
	Log Weight	0.0001	0.03	0.08	0.42	0.27	0.98

Species area curves

While a total of 79 sites were sampled inshore, only 43 were sampled offshore. This makes a direct comparison of species area curves difficult. For fish, about 188 species were collected inshore (Figure 2.29) and the curve did not seem to have reached an asymptote at about 80 sites. At 5 sites both inshore and offshore curves are equivalent for the cumulative number of fish species. At 40 sites, the offshore curve has a steeper rate of change and is higher than the inshore curve, suggesting that there may be more fish species offshore. The reverse is apparent for crustaceans (Figure 2.30) as the offshore curve had a lower number of species after 40 sites than did the inshore curves.

2.8.3.3 Results for fish

General description of the fish trawl catch

A total of 17.917 t and 374712 individual fish were caught by the fish trawl tows in the Far Northern Section of the great Barrier Reef over the two years of 1992 and 1993. This catch was made up of 224 teleost species, 10 species identified to family level and 22 elasmobranch species. The elasmobranchs consisted of 9 rays and 13 shark species. A full listing of the species caught during the two surveys are presented , along with percent occurrence, mean catch rate, mean size and standard deviation for fish, in Appendix 2.C.1.

The fish trawl tows also caught a number of invertebrates. Most of these were not identified to species. A total of 1.05 t and 3476 individual items of invertebrates were caught and these are listed in Appendix 2.C.2 along with the percent occurrence, catch rate and standard deviation.

Spatial analysis of fish communities

A total of 83 fish species were used in a principal component analysis to display the relationship between sites, based on their fish species composition. A plot of the scores of the first principal component (PC-1) against the scores of the second principal component (PC-2) is shown in Figure 2.31. The first and second principal components explained 27.8% and 7.2% respectively of the variation in association between sites. The third principal components explained 6.7% of the variation.

There is a marked difference in fish species composition between sites from different cross-shelf strata (Figure 2.31). The fish communities from sites in the two Inshore strata (A red squares and B brown triangles) overlap considerably, demonstrating close similarity. The overlap in fish communities from sites in the two offshore strata (D blue circles and E purple triangles) is less, but also indicates some similarity. However, the sites in each of the two sets of sites show complete separation, which suggests that the fish communities of the two most inshore strata show little similarity to the fish communities of the two most offshore strata. Furthermore, the sites in the central stratum (C green diamond and stars) show some separation from both of these groups of sites, but also partially overlap both the inshore and offshore strata. Fish communities at shallow sites, on shoals, in stratum C (green stars) and in deeper sites (green diamonds) are generally more similar to those from sites further offshore. Hence, the fish communities from the sample sites in the central stratum appear to be distinct from, but intermediate between, the inshore and offshore communities.

The sample sites in the study area were mapped as three groups based on their PC-1 scores (Figure 2.32). This demonstrates a spatial relationship of the sample sites based on their fish species composition. There is a strong cross-shelf pattern with offshore sites (blue circles, scores < –2.0) separating from inshore sites (red triangles, scores > 2.0). There is also a fairly distinct group of sites in the central inter-reefal strata—scores between –2.0 and 2.0—(yellow squares) which appears to resemble some of the most inshore or coastal sites.

The sample sites were mapped as two groups based on the scores of the second principal component, (Figure 2.33). These patterns of site distribution are not as strong as those from the first principal component, but some separation of sites based on their fish species composition can be seen. Sites with the shaded triangles are distributed over a large part of the study area. However, sites with the closed circles are mostly associated either with the offshore lagoon or with the southern region of the inshore channel. Within the inshore channel there is some evidence of latitudinal separation between the sites in the northern half of the study area (yellow squares) and those in the southern half (blue circles).

Principal component analysis was also used to show the relationship between fish species based on their abundance at sample sites, and the eigenvectors from the first and second principal components are plotted (Figure 2.34). Species that group together on this plot have similar patterns of abundance within the study area. The central group of closely clustered points—near (0, 0)—represent a large group of species that are relatively evenly distributed across all strata. Species not in or near this central group have more distinctive patterns of abundance throughout the study area. A table of the relative biomass of eight of the species with more distinctive patterns of abundance are presented (see Table 2.23). This table demonstrates a range of distribution patterns of species across the coastal shelf. The species that were abundant inshore, most abundant in the central sites (strata B and C) and with strongly decreasing abundance in the more offshore sites (strata D and E) are. *Torquigener pallimaculata* and *Nemipterus furcosus*.; The species that were most abundant in the inshore sites (strata A and B) but least abundant in the offshore sites are *Selar boops, Leiognathus* sp and *Leiognathus bindus*. Species that were most abundant in the offshore sites (strata D and E) are *Diagramma pictum* and *Lutjanus sebae*. A full list of the species and their biomas distribution patterns is given in Appendix 2.C.4.

Table 2.23 Mean weight(kg) of fish species caught by the fish trawler from each stratum in the study site of the Far Northern Section of the Great Barrier Reef.

			Stratum			
Species	**A**	**B**	**C**	**D**	**E**	**Total No**
Teleostii						
Choerodon sp. 2	0.16	0.26	0.46	0.19	0.04	775
Diagramma pictum	0.87	0.52	1.21	8.58	13.64	293
Leiognathus bindus	3.71	5.71	0.54	0	0	35133
Leiognathus sp.	25.89	34.96	6.25	0	0	123008
Lutjanus sebae	0.05	0.05	0.09	0	6.51	83
Nemipterus furcosus	3.88	5.65	8.02	4.9	0.29	7193
Pentapodus paradiseus	0.49	0.63	7.67	9.35	0.56	7228
Selar boops	2.72	8.94	0.98	0	0	7913
Selaroides leptolepis	15.44	41.46	9.72	17.07	0.2	77811
Siganus canaliculatus	2.58	3.73	1.86	0.48	0.29	6558
Torquigener pallimaculatus	0.28	1.12	0.23	0.03	0	1570

The results of the MANOVA for the station by species matrix, with 126 species present at 12 or more sites for 149 sites, was highly significant (P = 0.0001, Wilks' Lambda = 4.8796), which confirmed the differences in the biomass of species among strata that were seen in the unstructured analysis.

The combinations of strata that have the least within and greatest between variation is the combination of A/B/CD/E (Table 2.24). In this analysis of the bycatch data, strata C and D appear to be most similar suggesting four distinct cross shelf strata.

Table 2.24 Results of the MANOVA on fish trawl species to assess the amount of variation between groups and within groups. Adjacent strata have been combined into groups of 2 or 3 strata. The optimum combination is highlighted in bold text.

Group	F-Prob	No. of Groups	F-ratio	Numerator df	Denominator df
AB/C/D/E bet	$< 10^{-9}$	4	2.9485	246	190
AB/C/D/E wit	$< 10^{-1}$	4	1.703	82	63
A/BC/D/E bet	$< 10^{-9}$	4	2.7364	246	190
A/BC/D/E wit	$< 10^{-8}$	4	3.6394	82	63
A/B/CD/E bet	$\mathbf{< 10^{-9}}$	**4**	**3.4117**	**246**	**190**
A/B/CD/E wit	**0.231**	**4**	**1.1953**	**82**	**63**
A/B/C/DE bet	$< 10^{-9}$	4	3.1142	246	190
A/B/C/DE wit	$< 10^{-1}$	4	1.6272	82	63
AB/CD/E bet	$< 10^{-9}$	3	4.6376	164	126
AB/CD/E wit	$< 10^{-1}$	3	1.4346	164	126
AB/C/DE bet	$< 10^{-9}$	3	4.0721	164	126
AB/C/DE wit	$< 10^{-2}$	3	1.6645	164	126
A/BC/DE bet	$< 10^{-9}$	3	3.6057	164	126
A/BC/DE wit	$< 10^{-7}$	3	2.4803	164	126
A/BCD/E bet	$< 10^{-9}$	3	3.5267	164	126
A/BCD/E wit	$< 10^{-7}$	3	2.646	164	126
ABC/DE bet	$< 10^{-9}$	2	6.4391	82	63
ABC/DE wit	$< 10^{-8}$	2	2.2865	246	190
AB/CDE bet	$< 10^{-9}$	2	9.6415	82	63
AB/CDE wit	$< 10^{-4}$	2	1.6835	246	190

Cross-shelf patterns of occurrence of fish

Appendix 2.C.3 lists the frequency of occurrence of fish species in each stratum for species of which at least 200 (teleost fish) or 15 (elasmobranchs) individuals were collected. This shows that 31 of the fish species and one stingray occurred in all five strata. Twenty-one fish and one butterfly ray occurred in the three most inshore strata (A, B and C). Five fish and one stingray occurred in the three most offshore strata (C, D and E) and two fish and two sharks occurred in the two most inshore strata (A and B). The remaining fifteen fish occurred in various combinations of four of the five strata.

Within the sites sampled for fish, a total of 22 species of elasmobranch were caught, as were 224 species of teleost fish and 10 categories of fish grouped at the family level. Most of the 15 elasmobranchs and 124 fish species were found at fewer than five of the sample sites. Only one elasmobranch, the shark *Rhizoprionodon acutus*, was found in 10 or more sites. Only two species, *Lethrinus genivittatus* and *Nemipterus furcosus*, appeared in more than half of the sites sampled. The total number of each species found in each stratum is given in Appendix 2.C.5.

Catch composition and species richness of fish communities

Table 2.25 shows how many species were found in each of the five strata and in the groups of inshore and offshore strata. These are shown in bold type down the diagonal. For example, there were between 169 and 190 species in subsets of 19 sites in stratum A. The range of species numbers (in every case except stratum E and the offshore strata) comes from the 20 random subsets of 19 sites that were taken in each of the other strata in order to compensate for the unequal number of sites sampled in each stratum. Table 2.25 also shows how many species were in common between pairs of strata. For example, there were between 114 and 135 species in common between stratum A and stratum B.

There was a decline in the number of species from inshore (stratum A) to offshore (stratum E). There is a fairly high overlap in species among strata A, B and C. The overlap in species between A and B represents slightly more than 50% of the number of species found in A and B collectively. There are fewer species in common among strata that are further separated: for example only between 51 and 59 species are in common between strata A and E. The overlap in this case represents about 20% of the number of species found in A and E collectively.

Once strata A and B have been aggregated into inshore and C, D and E into offshore, the two regions differ very little in species richness, and the overlap contains just over 40% of the species found in the whole study area.

Table 2.25 Species richness for fish caught by the fish trawl in each stratum in the study site of the far northern Great Barrier Reef.

Stratum	A	B	C	D	E	Inshore	Offshore
A	**116-137**	76-86	76-94	42-57	37-45	**166-180**	111-119
B		**99-113**	64-84	38-49	36-42		**193**
C			**97-124**	57-67	46-56		
D				**93-105**	61-69		
E					**99**		
Total number of tows	19 of 42	19 of 40	19 of 28	19 of 23	19	70 of 82	70

The number and weight of all species at each site and in each stratum is also displayed. There are significant differences in the number of species among the cross-shelf strata ($p <$ 0.001; Table 2.26). These differences are clearly seen as a decrease in the number of species at each sample site as we moved offshore (Figure 2.35)

The total biomass of fish caught at each site also differed among strata ($p < 0.0001$; Table 2.26). More fish (by weight) were caught in the inshore strata (A and B) than in the offshore strata (C, D and E; Table 2.26), with the highest biomass of fish in stratum B (Figure 2.36).

Species–area curves are presented for the inshore strata (A and B) and the offshore strata (C, D and E; Figure 2.37) to show how well the sampling has represented the occurrence of species in these two areas. Although it appears that further sample effort would have collected some additional species of fish, both curves suggest that a greater sampling effort would not have produced a much greater number of fish species.

Table 2.26 Summary statistics from the ANOVA that compares the number of fish species and total biomass of fish ($\log_{10}$kg/tow) between the cross-shelf strata. (df = 4, 144)

		Stratum				
	p	**A**	**B**	**C**	**D**	**E**
Mean number of species per trawl	0.0001	29	30	21	16	18
Mean biomass ($\log_{10}$) of fish per trawl	0.0002	1.94	2.10	1.69	1.76	1.72

2.8.3.4 Results for benthos

General description of the dredge catch

A total of 7.2 t made up of 322172 items was caught by the Church dredge tows in the Far Northern Section of the Great Barrier Reef over the two years of 1992 and 1993. A total of 4681 sponges, 26771 cnidarians, 200591 molluscs, 5118 crustaceans, 66898 echinoderms and 13202 ascidian taxa were collected. A total of 687 species or groups were identified from the study area during the surveys. Most animals were identified to species level, but others could only be identified to higher levels (usually genus). A list of all species, their mean catch rates and the number caught are presented in Appendix 2.D.1. These consist of 2 species of seagrass, 84 types of sponge, 88 categories of Cnidaria, one group of polychaetes, 167 crustaceans, 225 molluscs, 24 bryozoans, 121 echinoderms, 54 ascidians, one sipunculid species.

Spatial analysis of benthic communities

A total of 172 benthos categories (mostly identified to species) were used in a principal component analysis to display the relationship between sample sites (n = 156) as based on the composition of benthos categories. A plot of the scores of the first principal component (PC-1) against the scores of the second principal component (PC-2) is shown in Figure 2.38. The first and second principal components explained 17.2% and 7.1% respectively of the variation in association between sites. The third, fourth and fifth principal components respectively explained 4.2%, 3% and 3% of the variation.

Figure 2.38 shows some differences in benthos category composition between sites from different cross-shelf strata. The benthic communities from sites in the two inshore strata (A red squares and B brown triangles) overlap considerably, demonstrating close similarity. The benthic communities from sites in the two offshore strata (D blue circles and E purple triangles) also overlap considerably. However, the sites from these two sets of sites only partially overlap, indicating that the benthos communities of the two most inshore strata are quite different from the benthos communities of the two most offshore strata. Furthermore, this partial overlap is only between stratum A and strata D and E. There is complete separation between the offshore strata and stratum B. The sites in the central stratum (C green diamonds and stars) overlap both the offshore and inshore strata. Although there is some overlap for a few sites, the community composition of the deep sites in stratum C seem to be similar to the communities in the inshore sites and the sites on the shoals seem to have communities similar to offshore sites. Hence, the benthic communities from the sample sites in the central stratum appear to be intermediate between the inshore and offshore communities.

Figure 2.39 shows the sample sites on the study area plotted as three groups based on their scores of the first principal component. This demonstrates a spatial relationship of the sample sites based on the composition of their benthos categories. There is a strong cross-shelf pattern with offshore sites (blue circles, scores < –2.0) separating from inshore sites (red triangles, scores > 2.0). The group of sites with scores between –2.0 and 2.0 (yellow squares) are distributed more widely, but mostly inshore, overlapping with sites with the highest scores.

Figure 2.40 shows the sample sites on the study area plotted as two groups based on their scores of the second principal component. These patterns of site distribution show some distinct grouping of sites based on the composition of benthic categories. Sites with the yellow squares (scores > 0) are distributed over a large part of the study area. However, sites with the blue circles (scores < 0) are mostly associated with the offshore lagoon (stratum E), or the southern and central region of the inshore channel (stratum B and southern stratum A).

The principal component analysis was also used to show the relationship between benthos species based on their biomass at sample sites, and the eigenvectors from the first and second principal components are plotted in Figure 2.41. Species that group together have similar patterns of abundance within the study site. The central group of closely clustered points—near (0, 0)—represent a large group of species that are relatively evenly distributed across all strata. Species not in or near this central group have more distinctive patterns of abundance throughout the study area. A table of the relative biomass and number of species with more distinctive patterns of abundance are presented in Tables 2.27 and 2.28. These show species that were most abundant in the inshore sites (strata A and B) but least abundant in the offshore sites (e.g. *Amusium pleuronectes*, *Astropecten* sp. 4, *Brissopsis* sp. 2, *Chicoreus cervicornisand Laganum* sp. 3); species that were most abundant in the central sites (strata C) and with strongly decreasing abundance in the more offshore sites (e.g. *Stellaster equestris*); species that were most abundant in the central sites and with strongly decreasing abundance in both inshore (strata A) and offshore sites (strata E e.g. *Sphaenopis* sp.1); species that were most abundant in the offshore sites (strata C,D and E) and least abundant in the inshore sites (strata A and B e.g. *Fungia* sp. 1, Crinoid sp.5, Crinoid sp.15 and Crinoid sp.17).

Table 2 27 Mean weight (kg) per tow for selected species of benthos within each stratum in the study area of the Far Northern Section of the Great Barrier Reef (1992-1993).

	Stratum					
Species	**A**	**B**	**C**	**D**	**E**	**Total no.**
Amusium pleuronectes	0.06	0.13	0.00	0.00	0.00	741
Astropecten sp. 4	0.01	0.02	0.01	0.00	0.00	704
Brissopsis sp. 2	0.02	0.03	0.01	0.00	0.00	773
Chicoreus cervicornis	0.01	0.03	0.00	0.00	0.00	663
Crinoid 15	0.00	0.00	0.28	0.57	0.35	3195
Crinoid 17	0.01	0.01	0.29	0.76	1.51	9823
Crinoid 5	0.01	0.00	0.30	0.32	1.37	6685
Fungia sp. 1	0.05	0.00	1.06	0.40	0.21	7269
Heart urchin 8	0.16	0.13	0.04	0.00	0.02	561
Laganum sp. 3	0.21	0.15	0.19	0.02	0.00	1052
Metrodira subulata	0.01	0.01	0.01	0.01	0.01	270
Sphaenopus sp. 1	0.15	0.29	0.78	0.58	0.24	10361
Stellaster equestris	0.13	0.11	0.35	0.08	0.03	898

Table 2.28 Mean number of selected species of benthos per tow within each stratum in the study area of the Far Northern Section of the Great Barrier Reef (1992-1993).

	Stratum					
Species	**A**	**B**	**C**	**D**	**E**	**Total no.**
Amusium pleuronectes	6	12	0	0	0	741
Astropecten sp. 4	4	11	3	0	0	704
Brissopsis sp. 2	5	12	3	0	0	773
Chicoreus cervicornis	5	10	2	0	0	663
Crinoid 15	0	0	25	71	34	3195
Crinoid 17	1	0	50	104	273	9823
Crinoid 5	0	0	39	39	216	6685
Fungia sp. 1	5	0	176	48	22	7269
Heart urchin 8	5	7	2	0	1	561
Laganum sp. 3	9	15	3	1	0	1052
Metrodira subulata	1	2	2	3	2	270
Sphaenopus sp. 1	9	22	153	138	52	10361
Stellaster equestris	5	5	12	3	2	898

The results of the MANOVA for the station by species matrix, with 131 species present at 15 or more sites for 157 sites was highly significant ($P = 0.0001$, Wilks' Lambda = 1.9742), confirming the between-stratum differences that were seen in the unstructured analysis.

The combinations of strata that have the least within and greatest between variation is the combination of A/B/C/DE (Table 2.29). In this analysis of the benthos data, strata D and E appear to be most similar resulting in four distinct cross shelf strata.

Cross-shelf patterns of occurrence of benthos

Appendix 2.D.2 presents the frequency of occurrence of 139 of the most abundant benthos species (at least 40 animals) in each cross-shelf stratum. Fifty-eight of these categories occurred in all five strata; 24 occurred only in the three most inshore strata (A, B and C), three occurred only in the two most inshore strata (A and B); four occurred only in the three most offshore strata (C, D and E); and two occurred only in the two most offshore strata (D and E). The remaining benthos categories appeared in various other combinations of the five strata. The number of each species/taxa within each stratum is given in Table 2.30.

Table 2.29 Results of the MANOVA on benthic invertebrate species/taxa to assess the amount of variation between groups and within groups. Adjacent strata have been combined into groups of 2 or 3 strata. The optimum combination is highlighted in bold text.

Group	F-Prob	No. of Groups	F-ratio	Numerator df	Denominator df
AB/C/D/E between	$< 10^{-2}$	4	1.8143	393	64
AB/C/D/E within	$< 10^{-3}$	4	2.7472	131	21
A/BC/D/E between	$< 10^{-2}$	4	1.6714	393	64
A/BC/D/E within	$< 10^{-3}$	4	3.5817	131	21
A/B/CD/E between	$< 10^{-3}$	4	2.0718	393	64
A/B/CD/E within	0.093	4	1.647	131	21
A/B/C/DE between	**$< 10^{-5}$**	**4**	**2.5364**	**393**	**64**
A/B/C/DE within	**0.701**	**4**	**0.8639**	**131**	**21**
AB/CD/E between	$< 10^{-2}$	3	1.8787	262	42
AB/CD/E within	$< 10^{-2}$	3	2.0793	262	42
AB/C/DE between	$< 10^{-3}$	3	2.5942	262	42
AB/C/DE within	0.041	3	1.5646	262	42
A/BC/DE between	$< 10^{-3}$	3	2.3024	262	42
A/BC/DE within	0.013	3	1.7779	262	42
A/BCD/E between	0.061	3	1.4864	262	42
A/BCD/E within	$< 10^{-3}$	3	2.6645	262	42
ABC/DE between	0.027	2	2.087	131	21
ABC/DE within	$< 10^{-3}$	2	2.0511	393	64
AB/CDE between	$< 10^{-3}$	2	3.7408	131	21
AB/CDE within	$< 10^{-2}$	2	1.6269	393	64

Catch composition and species richness of benthos communities

Table 2.30 shows how many species were found in each of the five strata and in the groups of inshore and offshore strata. These are shown in bold type down the diagonal. For example, there were between 307 and 360 benthic invertebrate species in subsets of 21 sites in stratum A. The range of species numbers (in every case except stratum E and the offshore stratum) comes from the 20 random subsets of 21 sites that were taken in each of the other strata in order to compensate for the unequal number of sites sampled in each stratum. Table 2.30 also shows how many species were common to pairs of strata.

Unlike the other two data sets, there is no decline in the number of benthic invertebrate species from inshore to offshore: strata A, C and D appear to be equally rich in species and the other two strata slightly less so. There is a fairly high overlap in species among strata A to D, with a reasonable overlap even between strata A and E. The overlap in species between A and B represents just under 50% of the number of species found in A and B collectively. The overlap between A and E amounts to about 25% of the number of species found in A and E collectively.

Once strata A and B have been aggregated into inshore and C, D and E into offshore, the offshore region appears to be richer in number of species than the inshore region, and the overlap contains about 40% of the 760 or so species represented in the whole study area (with stratum A represented by subsets).

Species–area curves are presented for the inshore strata (A and B) and the offshore strata (C, D and E) to show how well the sampling has represented the occurrence of species in these two areas (Figures 2.42). About 500 species of benthos were collected inshore and about 600 species offshore. Except for the sponges (Figure 2.42a), species of the other major taxonomic groups were better represented offshore. About 70 sponge species were collected inshore but only 50 offshore. The other sessile groups (Ascidians, Figure 2.42b and corals, Figure 2.42c) ranged from about 45 inshore to 700 offshore, except for the bryozoans (Figure 2.42d), which reached just over 20 species offshore. Molluscs (Figure 2.42e) were the most diverse group, with 130 species inshore and 170 0 offshore, closely followed by the crustaceans (Figure 2.42f), with 100 species inshore and about 135 offshore.

Table 2.30 Species richness for benthic invertebrate community from the study site in the Far Northern Section of the Great Barrier Reef.

Stratum Benthos	**A**	**B**	**C**	**D**	**E**	**Inshore**	**Offshore**
A	**307-360**	183-218	169-202	146-175	114-132	**504-513**	335-340
B		**274-308**	159-193	130-158	92-109		**608**
C			**330-368**	193-213	143-168		
D				**333-364**	176-189		
E					**286**		
Total number of tows	21 of 41	21 of 40	21 of 31	21 of 24	21	76 of 81	76

The mean biomass per station within each stratum is given in Appendix 2.D.3. This table shows the relative distribution of the mean weight per species/taxa across the shelf (strata) from inshore to offshore where there were more than 100 species/taxa caught. Most of the mass of the cnidarians was caught in strata C and D. Crustacean biomass was greatest in stratum C and that for bivalves in strata A and B. The holothurian biomass was concentrated mostly inshore and for Ophiuroids offshore. The ascidians biomass was distributed over all strata.

The mean number of benthos species at each site and in each stratum is also displayed in Table 2.31 There are significant differences in the number between the cross-shelf strata ($p<0.0001$; Table 2.31). The main difference appears to be a decrease in the number of species in the offshore strata (D and E), especially in the offshore lagoon (stratum E; Figure 2.43).

Table 2.31 Summary statistics from the ANOVA that compares the number of benthos categories and total biomass of benthos between the cross-shelf strata. (df=4,151) in the study site in the Far Northern Section of the Great Barrier Reef.

	p	Stratum A	Stratum B	Stratum C	Stratum D	Stratum E
Mean number of benthic categories per trawl	0.0001	49	49	46	44	30
Mean biomass ($\log_{10}$) of benthos per trawl	0.0007	0.59	0.69	0.96	1.06	0.97

The total biomass of benthos caught at each site also differed between strata ($p<0.0001$; Table 2.31).. More benthos (by weight) was caught in the offshore strata (C, D and E) than the inshore strata (A and B) with the highest biomass of benthos in stratum D (Figure 2.44).

2.8.4 Discussion

This is the first extensive study of the prawns, fish and benthos from across the coastal shelf in the Far Northern Section of the Great Barrier Reef. Previous studies have dealt mainly with the central section of the Great Barrier Reef. These studies have also been on a more limited scale. The most relevant comparable reports are those of Birtles and Arnold (1983, 1988), Cannon et al. (1987), Jones and Derbyshire, 1987, Watson and Goeden 1989, Watson et al 1990 and Coles et al. 1996 who studied various sections of the Great Barrier Reef. Cannon et al. (1987) found, like the present study, that the distribution of benthos correlates with distance from shore (longitude) and is influenced by sediment type. Three distinct site assemblages of demersal trawl fauna were identified in the central Great Barrier Reef region (Watson and Goeden 1989). These assemblages were coastal, inshore and inter-reefal. The distribution of these assemblages was related to water depth, distance offshore and sediment particle size. Watson and Goeden (1989) did not sample the offshore (outer lagoon) region.

Prior studies of inter-reefal fauna in the Great Barrier Reef

Birtles and Arnold (1983 & 1988) used a 1.6 m epibenthic dredge to sample inter-reefal epibenthos during a series of integrated studies at up to ~90 sites, on a roughly 8 n.mile grid off Townsville, at various intensities between 1977 and 1983. Most sites were in the GBR lagoon area, between the coast and the reef-matrix, although a few sites were sampled on the outer half of the shelf, amongst the reefs. Multivariate community analyses clearly showed cross-shelf zonation in fauna. There was a shallower (<20 m) inshore zone, to about 30 n.miles offshore characterised by resuspended terrigenous muddy deposits, with low species richness of carnivorous and deposit feeding echinoderms, molluscs, crustaceans, fish, bryozoans and algae, and low species evenness — ie. a relatively low number of species was dominated by even fewer. Further offshore, from ~30 n.miles to the mid-shelf reef-matrix at ~80 n.miles, the main lagoon zone was characterised by deeper water (20-50 m) and less muddy sediments dominated by coarse sand and rubble, primarily of biological origin, with higher species richness of all faunal groups. In part, this increased diversity was due to increased habitat heterogeneity in terms of patches of harder substratum that allowed a wide variety of suspension feeders, such as sponges, ascidians, crinoids, holothurians, and bryozoans, to gain a foothold in addition to the deposit feeders in the sediments between the patches. On the outer half of the shelf (> ~80 n.miles), in the offshore inter-reef zone the fauna changed again, with less fine sediment, more harder patches, and greater depth. A time series of six years was available for echinoderms at selected sites. For these fauna, patterns of distribution and abundance remained essentially stable over the period. Greatest variability was apparent in the nearshore sites, due to physical instability of the sediments caused by wind generated waves.

Cannon, Goeden and Campbell (1987) conducted classification and ordination analyses of trawl bycatch (fishes and macro & mega benthos) from two of a series of seven exploratory trawl surveys from three main areas of the GBR. Samples were collected primarily with 2 m try-shot nets at about 230 sites between 1979 and 1982. Although providing significant latitudinal coverage, most sampling was unstructured, with the objective of identifying new commercial prawning grounds. However, one survey in particular, provided replicated cross-shelf samples off Cairns. Trawl series I covered ~6° of latitude, from ~12°S to 18°S, but cross-shelf effects were not controlled for and data could only be analysed in binary form (presence or absence). Analysis of series I at several taxonomic levels generally separated the sites into three main groups, but the groupings did not correspond to any clear geographic pattern, except that sites from Princess Charlotte Bay usually were separated. There appeared to be no major latitudinal differences, the patterns were interpreted as weak cline, or continuum — however, the authors treated this result with caution given the uncontrolled nature of the sampling. Trawl series V was more rigorously conducted, with three replicate cross-shelf transects ~20 n.miles apart with five representative and quantitatively sampled sites along each transect, from the inshore, lagoon and offshore inter-reef zones. The samples and the classification and ordination were dominated, not surprisingly given the sampling method, by fishes. Nevertheless, the results were qualitatively similar to those of Birtles and Arnold: the sites split into three main groups, inshore and offshore inter-reef with a transition zone in the lagoon between. The inshore zone was much less diverse than the offshore inter-reef zone; and these patterns were correlated with physical factors changing from inshore to offshore, ie. increasing depth and from fine terrigenous to coarser carbonate sediments.

Watson and Goeden (1989) used commercial prawn trawl gear to sample fauna at monthly intervals in 20 sites distributed from the inshore, across the lagoon, into the offshore inter-reef matrix, over a ~1°x1° region off Townsville in 1985. Classification analysis showed very consistent group membership of sites, despite seasonal variation — the faunal composition of the samples consistently grouped the sites into inshore, lagoonal and offshore inter-reef zones similar to that of Birtles and Arnold. However, species richness appeared to be greater inshore than offshore, with 82% of the 200 species analysed present in the coastal zone, 80% in the inshore zone and 70% in the offshore. Interestingly, the coastal zone received ~5x less commercial trawling effort than the other zones. As with the other studies, these patterns were correlated with the physical factors depth, sediments and carbonate content.

Coles, Lee-Long and co-workers (1996) conducted a video survey over ~4° of latitude north of Cairns, primarily for broad scale mapping of seagrass, but sediment, algae and epibenthic megafauna were also recorded. The sampling strategy for the survey was to divide the region into 15-minute-of-latitudinal blocks and select a cross-shelf transect at random from each block; each transect was divided into 1 n.mile segments and a randomly placed video transect ~100-300 m long was conducted in each segment. The patterns observed concurred with patterns documented by others: most megafauna were observed offshore on harder substratum, which were also areas that were trawled less. Algal beds (*Caulerpa* & *Halimeda*) and solitary corals were also more abundant offshore. A lagoonal area near the

Turtle Group of islands was also sampled. This area was not trawled due to dense seagrass beds — large numbers of sponges were observed in this area.

The above studies showed that the least diverse areas had muddier sediments, where the dominant animals were deposit feeders. Sandier and harder areas tended to be more diverse, at least partly because of the greater range of physical habitats. The fauna of harder areas were also more abundant, and the dominant animals were filter feeders, scavengers or carnivores. The megabenthic epifauna, which form living structural habitat attached to the seabed, generally were restricted to rubbly or rocky patches, or areas where the bedrock or coarse substrata were exposed by fast currents. Such patterns are also typical of other regions (eg. Torres Strait: Pitcher et al. 1992; Gulf of Carpentaria: Long and Poiner 1994, Long et al. 1995).

The various studies have shown that there is a distinct cross-shelf zonation of benthic fauna in the GBR. This zonation is a consequence of the physical habitat requirements of the fauna and is a reflection of the change from terrigenous muddy sediments of the inshore lagoon through to coarse calcareous sediments of the offshore inter-reef. Typically, multivariate analyses separated the fauna into three main groups: inshore lagoon, offshore inter-reef, and a mid-shelf lagoon transition area. This zonation was apparent in all the GBR studies, although the composition of the species groups among the different studies has not been examined for consistency. Only one of the studies (Cannon et al. 1987) compared samples from a range of latitudes (~12°S to ~18°S) and showed an overlapping continuum rather than discrete groupings of (prawn trawl bycatch) faunal variation. However, the authors treated this result with caution due to their unstructured sampling strategy.

Our studies of inter-reefal fauna in the Great Barrier Reef

Prawn communities

The penaeids, like the fish and benthos, show the same strong correspondence with substratum distribution as was found in the above studies. The commercially important species are found in the inshore region where the substratum is composed of mud and sand. The only exception is the red-spot king prawn (*Penaeus longistylus*), which is more abundant among the sandy coraline substrates of the mid-shelf region. The spatial distribution of commercially exploited penaeids in the Gulf of Carpentaria is thought to be substrate dependent (Somers 1994) rather than substrate independent.

The principal component analysis of the prawn data showed a definite gradient from the inshore lagoon through to the mid-shelf reef–shoal zone. The prawn species did not occupy exclusive areas; distributions overlapped considerably and most species ranged over a wide area of the cross-shelf transect but displayed concentration(s) in abundance and biomass in particular habitat zones. The relatively large-scale spatial gradients in the species abundance and biomass data were interpreted as being due to sediment or habitat preferences of each species, and hence being location dependent. The smaller-scale structures within the preferred habitat areas were interpreted as being due to aggregation or schooling, which was location independent.

Compared with other north Australian prawn fisheries, the Shelburne Bay region is only a small fishery (Table 2.06), but with good daily catch rates. Not surprisingly, the inshore and reef–shoal regions where the commercial prawns occur are fished most heavily. The boats can fish between the reefs and shoals well out into stratum C north of the Cross-Shelf Closure. In Princess Charlotte Bay and at Townsville, the inshore lagoon between the reef-shoal matrix and the coast is also the most intensively fished.

Fish and benthic communities

In our study, the fish (from the prawn and fish trawler) and benthos (from the prawn trawler and dredge) in the cross-shelf region of the Far Northern Section of the Great Barrier Reef split into two major communities: an inshore community (the inshore lagoon) and an offshore community (consisting of the mid-shelf inter-reef and the outer lagoon). Within the inshore lagoon, there are differences between the community in the section near the coast (stratum A) and the rather muddier section to the east of it (stratum B, Table 2.32). There are also differences among the communities in the offshore region: the eastern region (stratum E) being characteristic of communities seen on calcareous, *Halimeda*-derived substrata, while the community in the mid-shelf region (strata C and D) represents a hybrid of inshore and offshore communities—a transitional region. This hybridisation is possibly due to the depth stratification in this region. Some of the samples from this region came from the tops of the shoals and others from the channels in between the shoals. Samples from the tops of the shoals are more closely aligned with the samples collected further offshore and those from the channels with those from inshore. Bycatch communities were most similar in strata B and C, fish communities were most similar in strata A and B and strata C and D, while benthos communities were most similar in strata D and E. There are no distinct boundaries, rather a continuum of change across the strata. This continuum lends itself to a five stratum model across the shelf (see Table 2.45).

Table 2.32 Summary of results of the ANOVA to find the combinations of strata in the study area of the GBR that have the lowest within stratum variation and greatest between strata variation. (bet = between, wit = within, Num = numerator, Den = denominator.)

Group	F-Prob	No. of Groups	F-ratio	Num. df	Den. df
Bycatch					
A/BC/D/E between	**$<10^{-9}$**	**4**	**4.1372**	**291**	**64**
A/BC/D/E within	**0.059**	**4**	**1.8207**	**97**	**21**
Fish					
A/B/CD/E between	$<10^{-9}$	4	3.1142	246	190
A/B/CD/E within	$<10^{-1}$	4	1.6272	82	63
AB/CD/E between	**$<10^{-9}$**	**3**	**3.4117**	**166**	**126**
AB/CD/E within	**0.231**	**3**	**1.1953**	**166**	**126**
Dredge					
AB/C/DE between	$< 10^{-3}$	4	2.0718	393	64
AB/C/DE within	0.093	4	1.647	131	21
A/B/C/DE between	**$< 10^{-5}$**	**4**	**2.5364**	**393**	**64**
A/B/C/DE within	**0.701**	**4**	**0.8639**	**131**	**21**

There is no single pattern of distribution of species across the shelf. The abundance of some species decrease from inshore to offshore; while other groups have the opposite pattern. Some groups were found quite rarely, but spread throughout the study area; while other groups were apparently more restricted in their distribution. Generally, benthic groups (invertebrates from the prawn and fish trawls and the dredge) contained members of all major taxonomic classes.

In our study, the most abundant species in the prawn trawl bycatch were the fish species *Leiognathus* sp. (inshore), *Lethrinus genivittatus*, *Nemipterus furcosus*, *Pentapodus paradiseus*, *Pristotis jerdoni* (offshore), *Scolopsis taeniopterus and Selaroides leptolepus* (both inshore) and the crabs (*Portunus tenuipes*, *Portunus rubromarginatus*). A number of species common to all strata were reported as being abundant in more southerly latitudes—two fish (*Engyprosopon grandisquama*, *Paramonacanthus japonicus*) and the portunids (*P. tenuipes*, *P. rubromarginatus*) were the most numerically abundant species off the Townsville region (Watson et al. 1990). In Torres Strait, to the north, *Nemipterus furcosus* was the most abundant fish species in prawn trawler bycatch.

The fish composition of the discards was different from the fish composition in Albatross Bay (Weipa), on the western shore of Cape York, but similar to the fish composition in the Torres Strait. In Albatross Bay, the leiognathids dominated the composition of trawls (Blaber et al. 1990): about 28% of biomass at night. In our study on the east coast, the leiognathids made up only 2% of the fish biomass. In the Torres Strait they made up between 1 and 1.8% of the fish biomass of trawl catches (Harris and Poiner 1990). Many of the fish species that are common in Albatross Bay and the Gulf of Carpentaria such as *Anodontostoma chacunda*, *Drepane punctata*, *Polynemus multiradiata* and the Pomadasids were not caught in our study, probably because no major rivers discharge into the reef area of the Far Northern Section of the Great Barrier Reef.

In all, 247 fish species were recorded from 122 tows in our prawn trawl bycatch samples. This compares with 237 fish species in Albatross Bay from 118 tows (Blaber et al. 1990) and 233 fish species in 85 tows off New Caledonia (Kulbicki and Wantiez 1990). Our samples were collected from two sampling periods over two years and are by no means exhaustive. A comparison of fish trawl catches with prawn trawl catches in the study area showed that neither the prawn trawler nor the fish trawler, as a single sampling tool, catches all the species present (Wassenberg et al. 1997). In our surveys, we combined the fish data for both devices. All of the large sharks, as well as the larger fish (lutjanids, epinephalids), caught during the survey were taken in the fish trawl.

The number of species per trawl was highest inshore for all devices (fish, prawn trawl and dredge), decreasing for offshore samples (Table 2.33). Biomass per trawl showed a similar pattern, except for the dredge, in which the biomass per trawl was higher offshore. The larger biomass per tow offshore in the dredge may be attributed to large sponges or boulder corals. Regionally a different picture emerged: the total number of species was generally higher in the offshore region than the inshore region. Nonetheless, despite being the area where trawling intensity is highest, the inshore region supports a community almost as diverse as the offshore region.

Table 2.33 Summary data of fish bycatch, benthos and prawn composition for inshore and offshore regions of the Far Northern Section of the Great Barrier Reef. (with average biomass and numbers per trawl, with * = number of species standardised for equal number of stations). Prawn to bycatch ratios ranged from 1:6 inshore to 1:10 offshore.

Target group	**Inshore**	**Offshore**	(*p*)
Prawns	(n = 79)	(n = 43)	
Biomass per trawl (kg)	2.6	1.4	0.8428
Number of species per trawl	5	5	0.8064
Total number of species	9	11	
Bycatch			
Biomass per trawl (kg)	16.3 (1.06)	14.3 (1.08)	0.2062
Number of species per trawl	52	36	0.0001
Total number of species	275 (211)*	215	
Fish			
Biomass per trawl (kg)	109 (1.09)	57 (1.09)	0.0001
Number of species per trawl	51	32	0.0001
Total number of species	254 (233)*	263	
Dredge			
Biomass per trawl (kg)	4.3 (1.14)	9.9 (1.14)	0.0001
Number of species per trawl	49	41	0.0013
Total number of species	517 (513)	608	

adjusted to produce a comparable number of stations

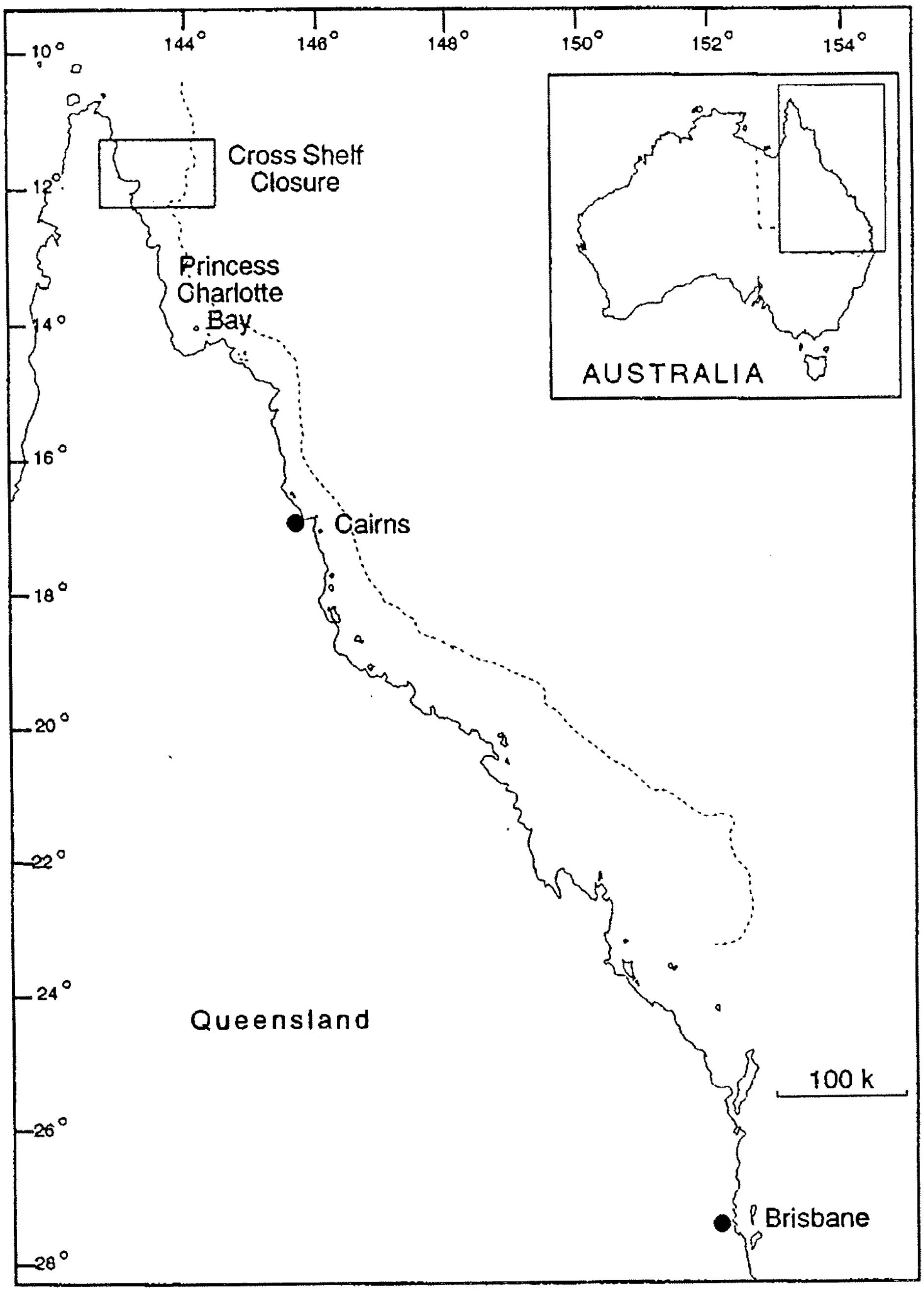
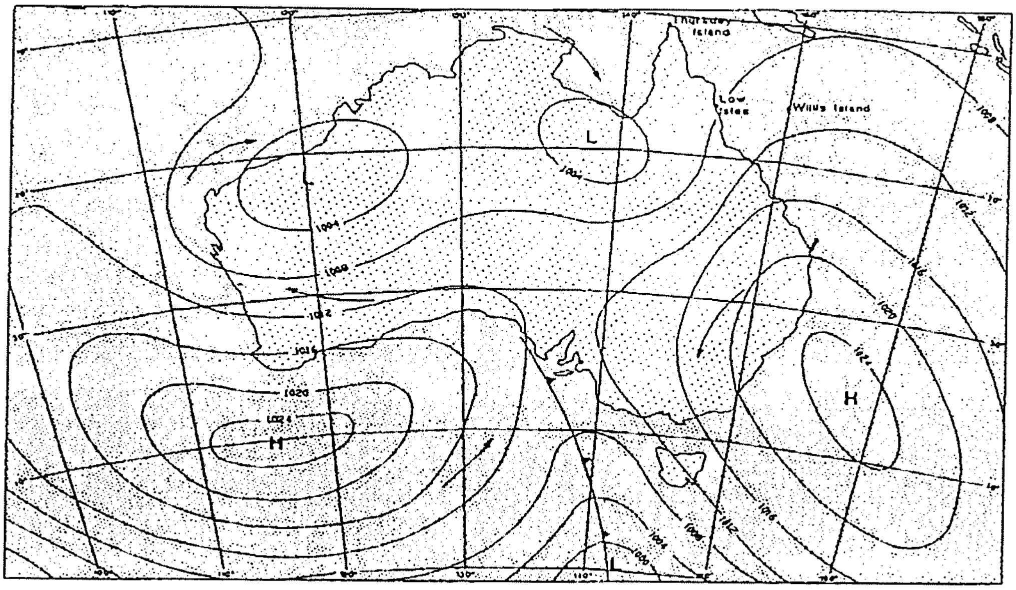
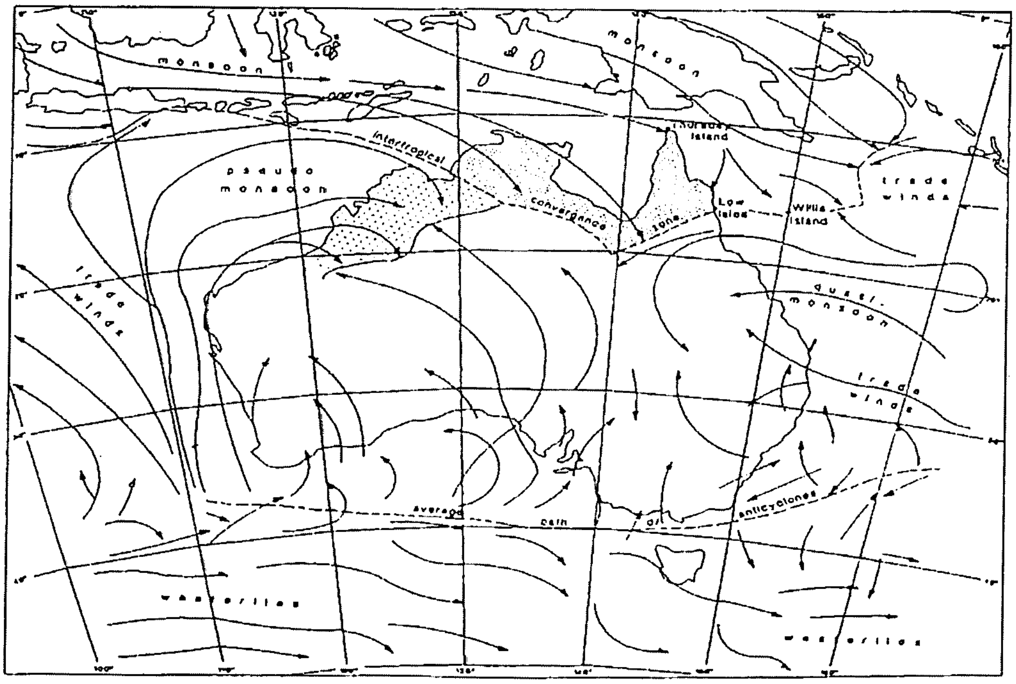


Figure 2.01 Map of the Queensland coastline showing the portion with the Cross-Shelf Closure study area.

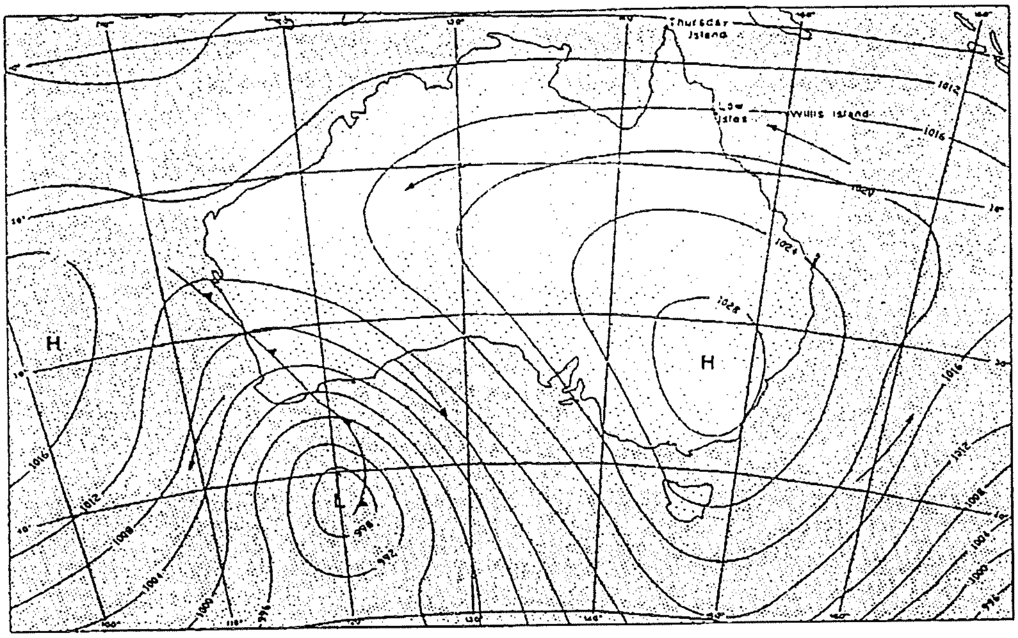


TYPICAL SYNOPTIC SITUATION - SUMMER (Source: Atlas of Australian Resources, 1986)

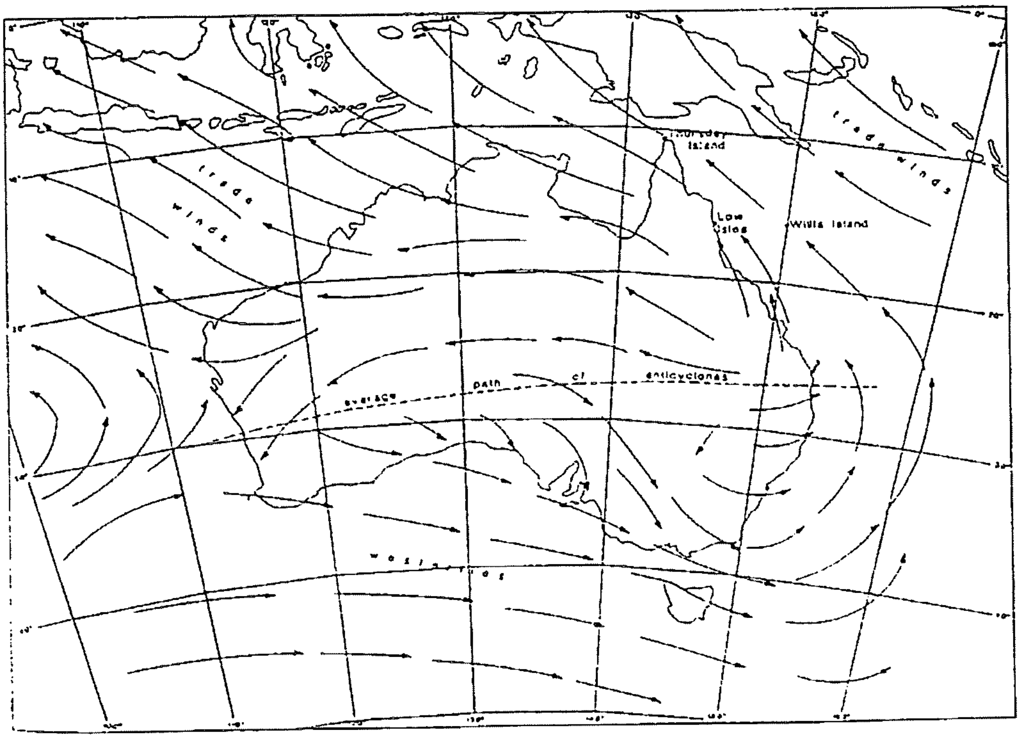


GENERALISED CIRCULATION - JANUARY (Source: Atlas of Australian Resources, 1986)

Figure 2.02 Typical summer weather patterns for Australia

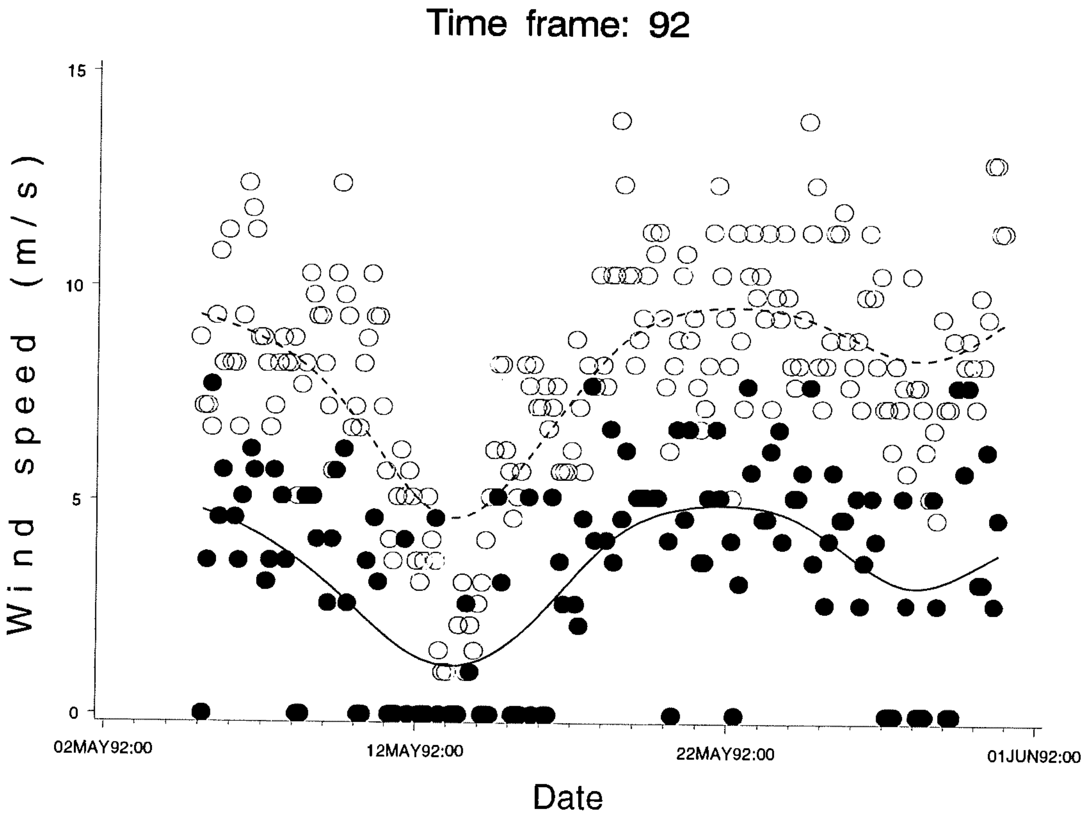


TYPICAL SYNOPTIC SITUATION - WINTER (Source: Atlas of Australian Resources, 1986)

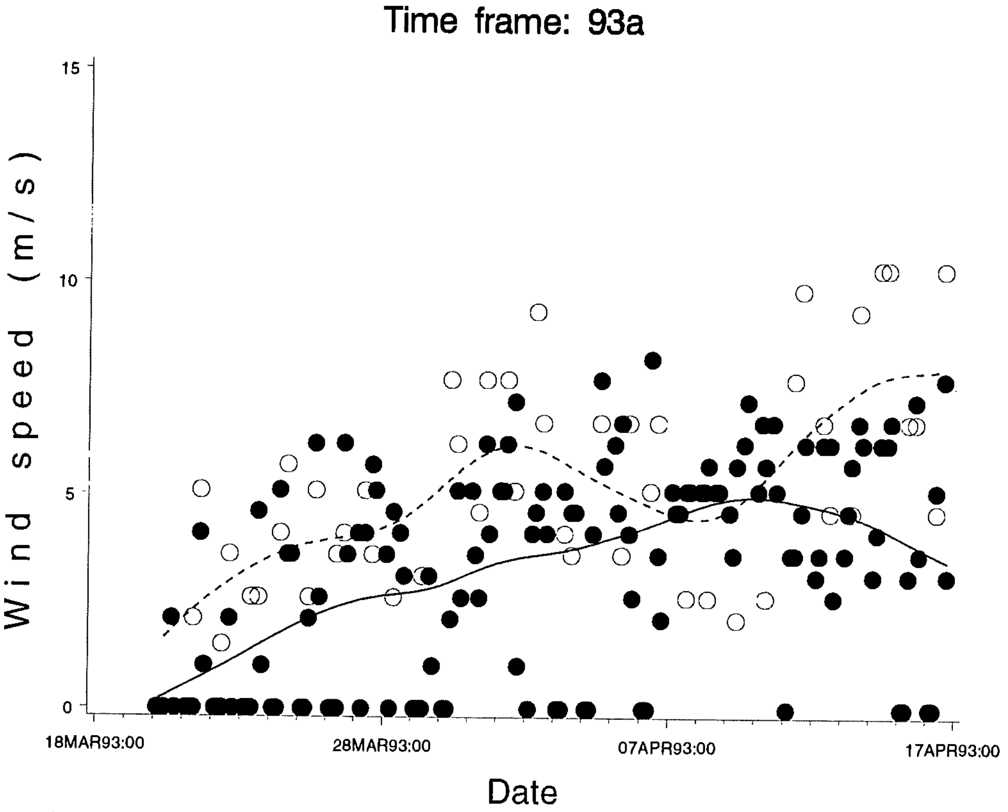


GENERALISED CIRCULATION - JULY (Source: Atlas of Australian Resources, 1986)

Figure 2.03 Typical winter weather patterns for Australia

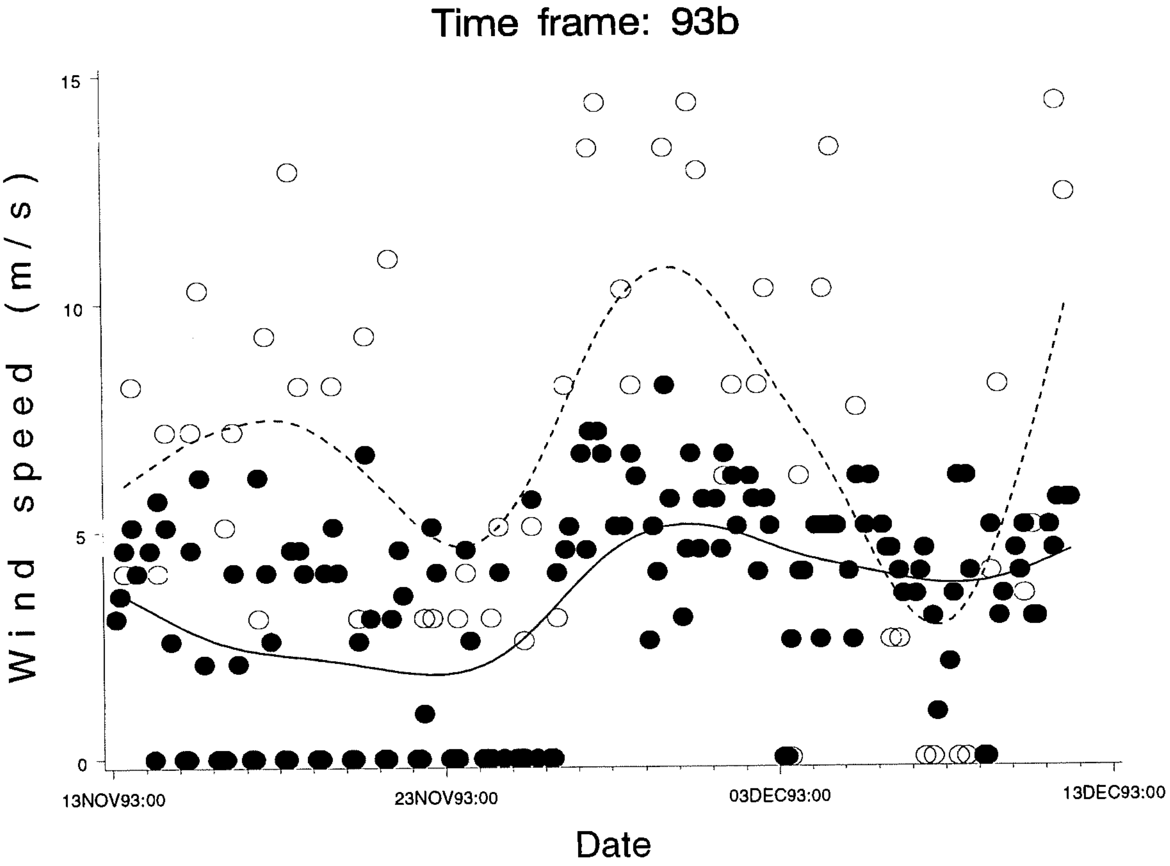


(a) First survey 1992

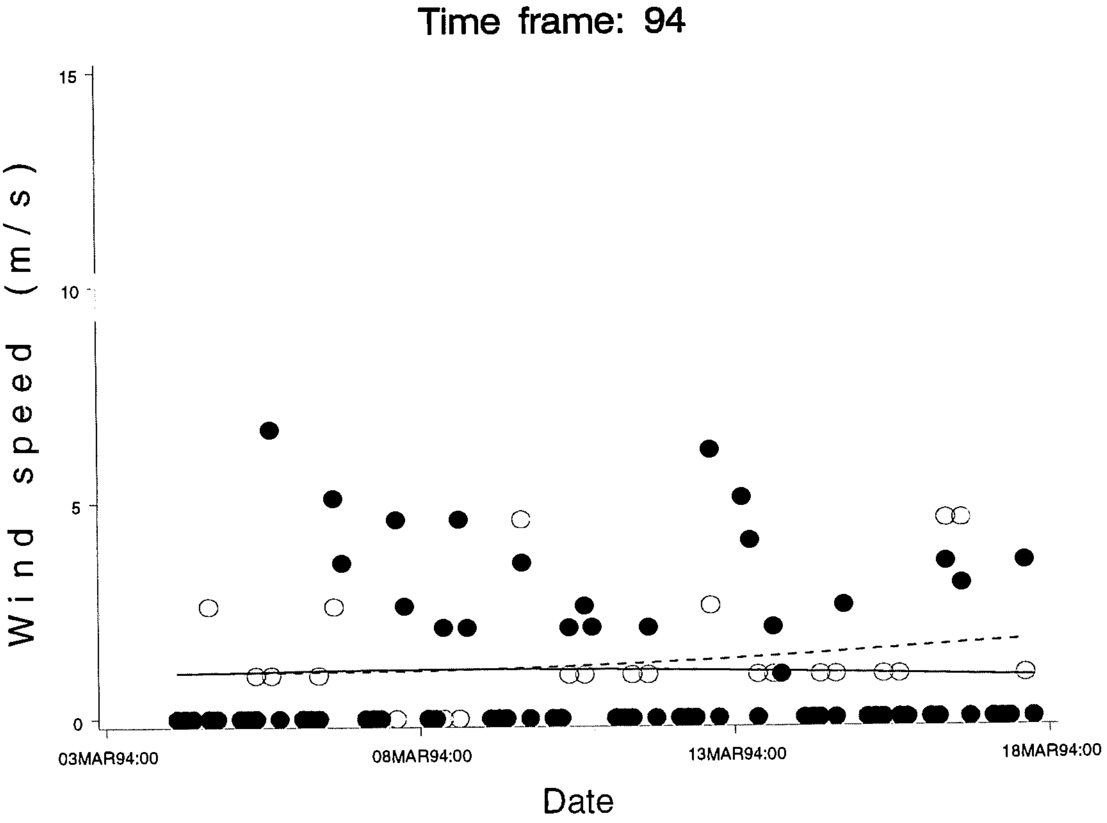


(b) Second survey (open v closed)

Figure 2.04 (a) Wind speed data for the Torres Strait (open circles) and Lockhard River (closed circles) with smoothing curves during the sampling cruises to the Far Northern Section of the Great Barrier Reef. (0.51 m/s = 1 knot).

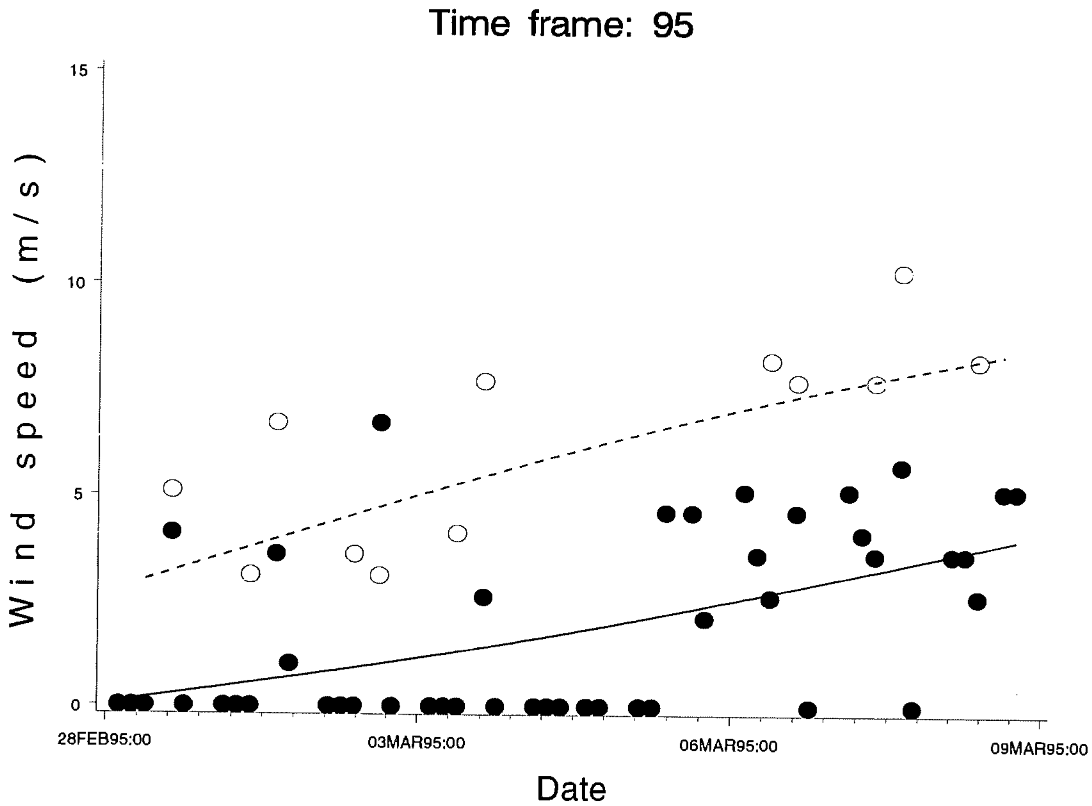


(c) Start of the BACI experiment



(d) Middle of the BACI experiment

Figure 2.04 (b) Wind speed data for the Torres Strait (open circles) and Lockhard River (closed circles) with smoothing curves during the sampling cruises to the Far Northern Section of the Great Barrier Reef. (0.51 m/s = 1 knot).



End of the BACI experiment

Figure 2.04 (c) Wind speed data for the Torres Strait (open circles) and Lockhard River (closed circles) with smoothing curves during the sampling cruises to the Far Northern Section of the Great Barrier Reef. (0.51 m/s = 1 knot).

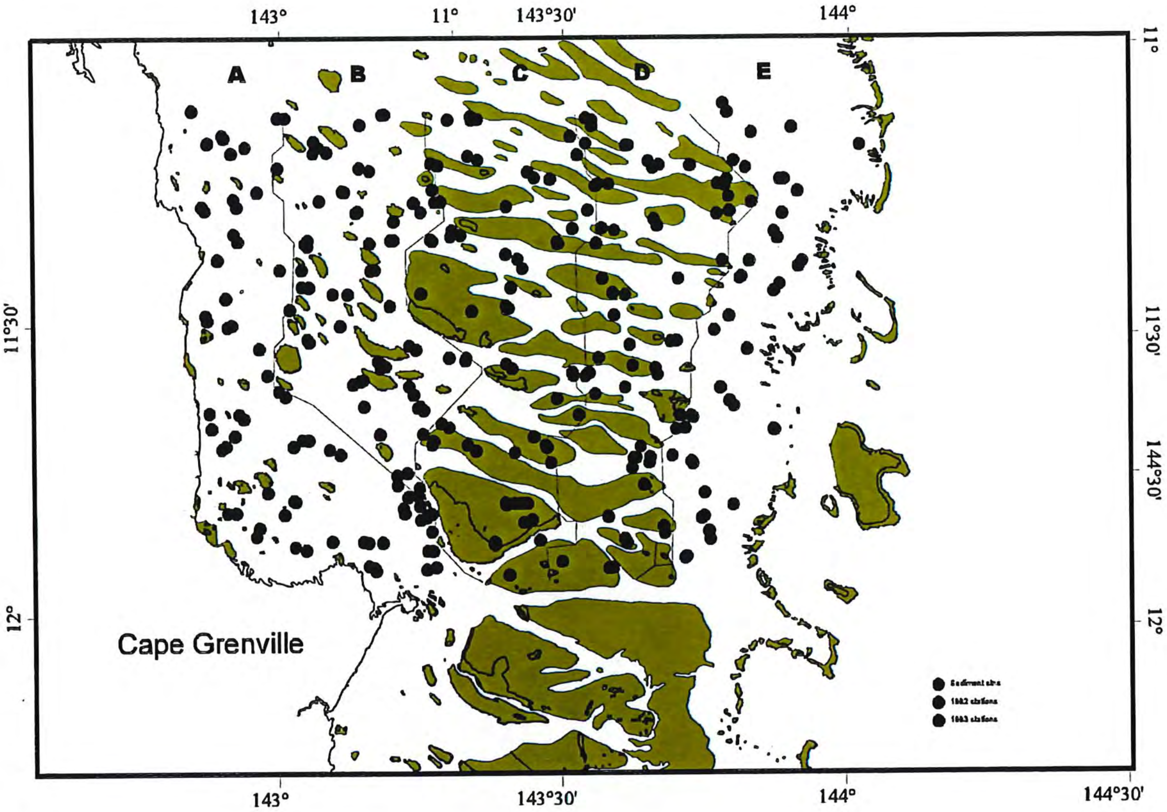


Figure 2.05 (a) The study area, showing sediment sampling sites and the five habitat zones or strata (A-E) defined for the study site and the Green Zone in the Far Northern Section of the Great Barrier Reef.

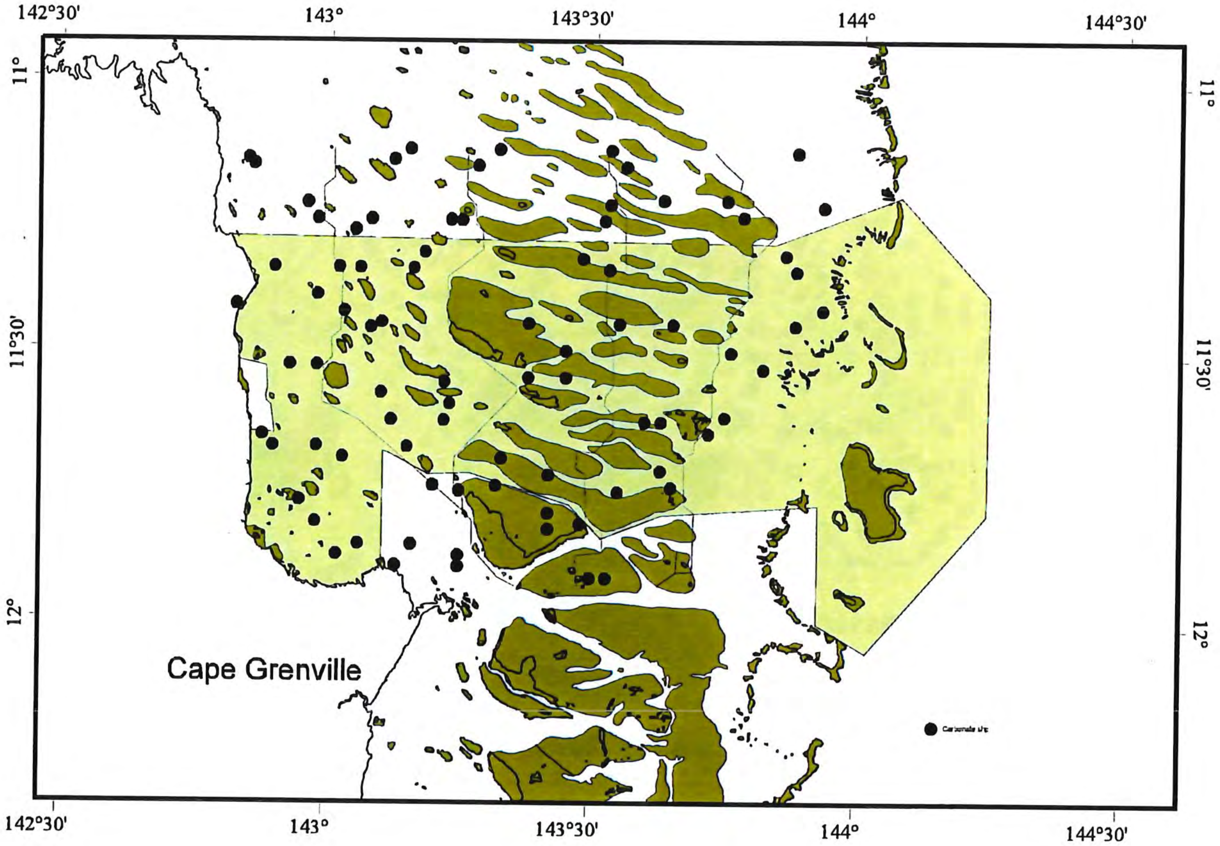
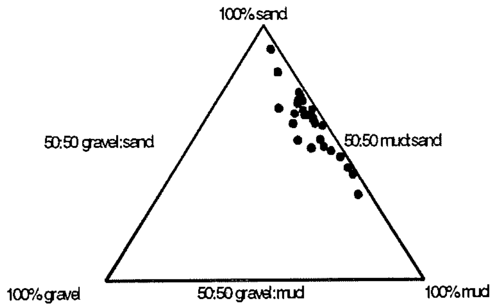
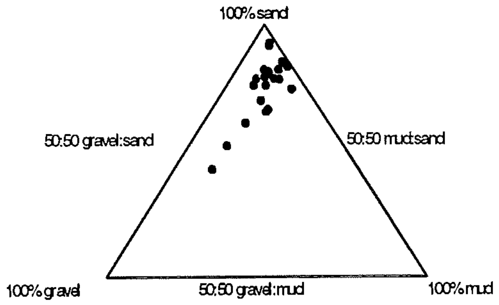


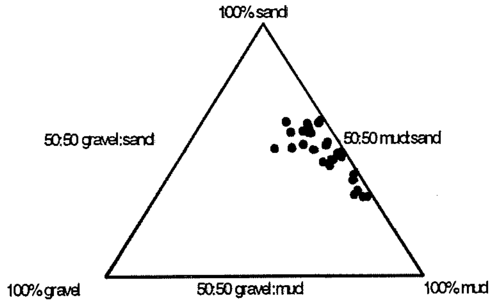
Figure 2.05 (b) The study area, showing carbonate sampling sites and the five habitat zones or strata defined for the study site and the Green Zone in the Far Northern Section of the Great Barrier Reef.



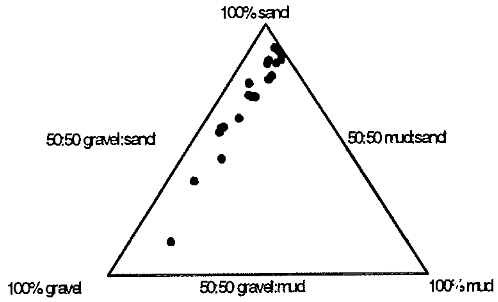
Stratum A



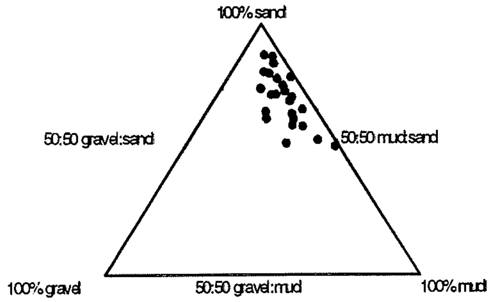
Stratum D



Stratum B



Stratum E



Stratum C

Figure 2.06 Ternary diagrams for percentage sediment composition for each of the five strata in the study site of the Far Northern Section of the Great Barrier Reef.

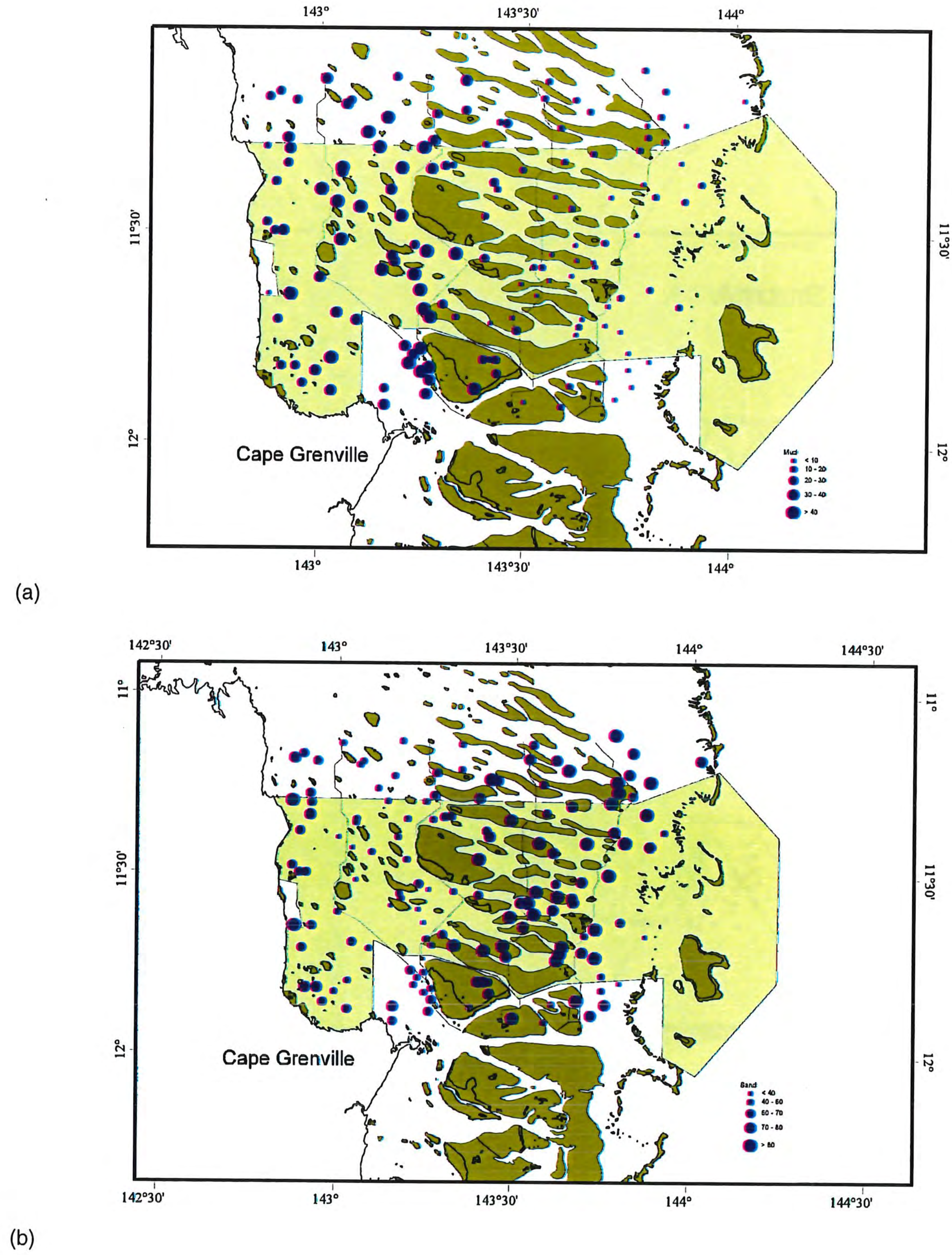
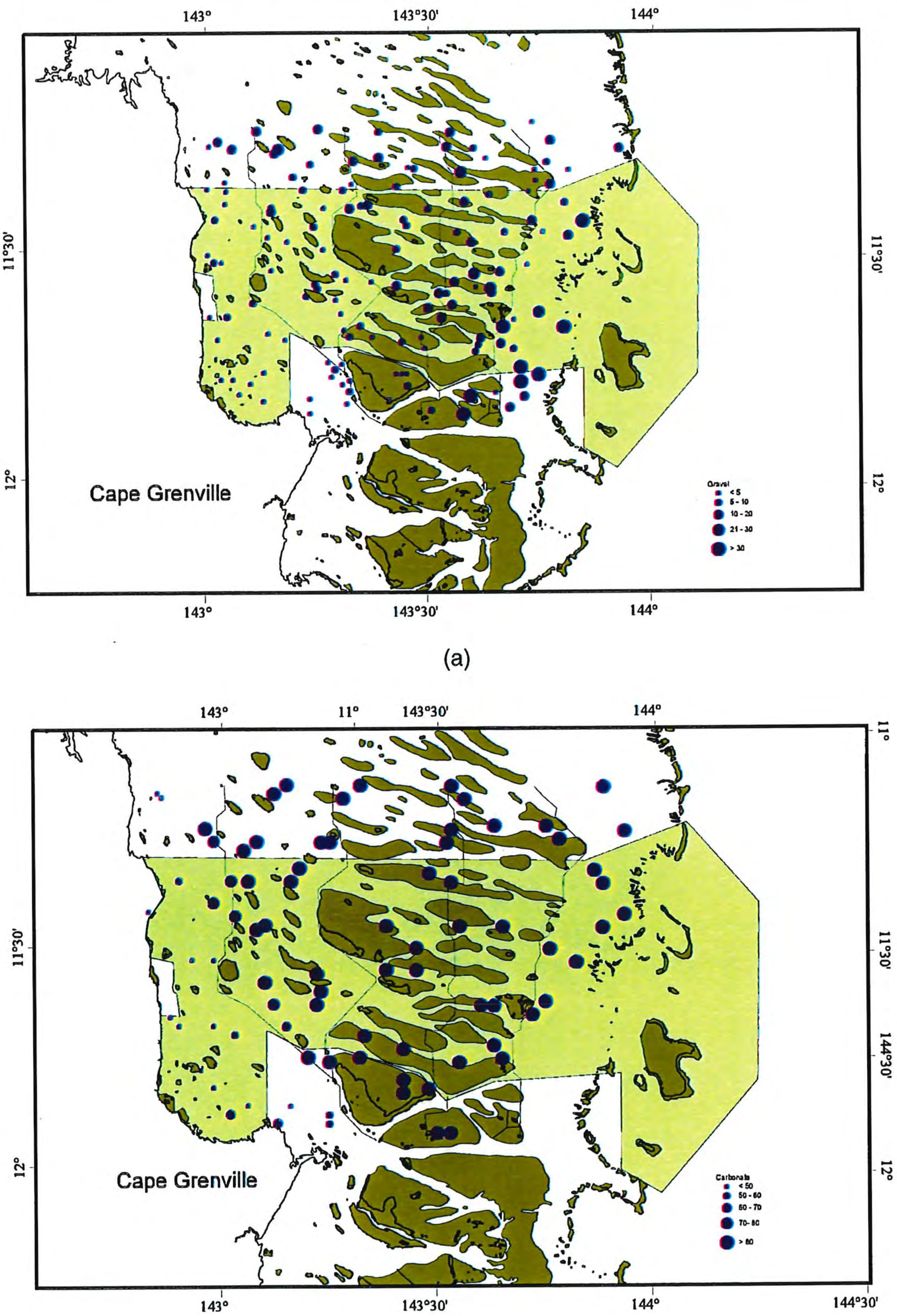


Figure 2.07 **(a)** Maps of sediment composition showing distribution of percentages of (a) mud (<0.063 mm), (b) sand (0.063–2.0 mm) in the study area of the Far Northern Section of the Great Barrier Reef.

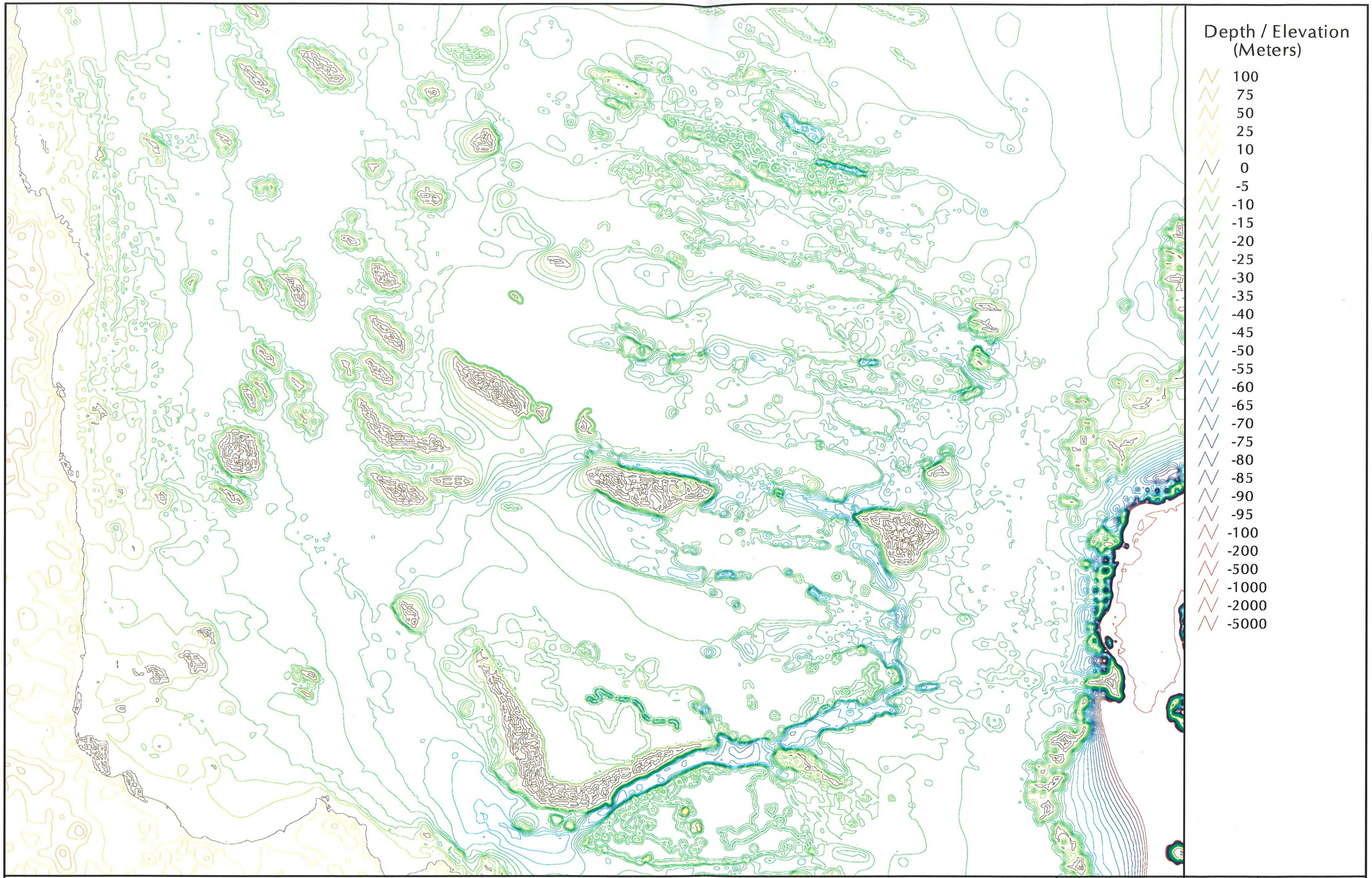


(a)

(b)

Figure 2.07 (b) Maps of sediment composition showing distribution of percentages of (a) gravel (> 2.0 mm) and (b) carbonates in the study area of the Far Northern Section of the Great Barrier Reef.

Figure 2.08 Bathymetric map of the study area in the Far Northern Section of the Great Barrier Reef.



Scale 1:400000

kilometres

5 0 10 20 30 40 50

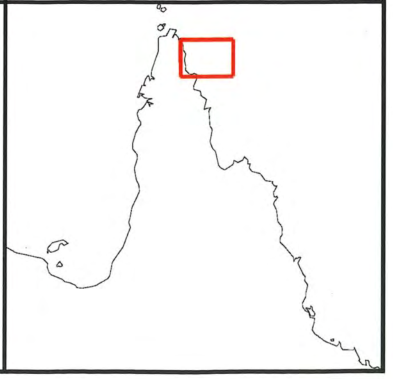
WARNING: Not for Navigational Use

Sources: CSIRO Marine Research

Bathymetric Contour Map
Figure 2.08

Location of the site is in the Far Northern section of the Great Barrier Reef.

CSIRO
MARINE RESEARCH



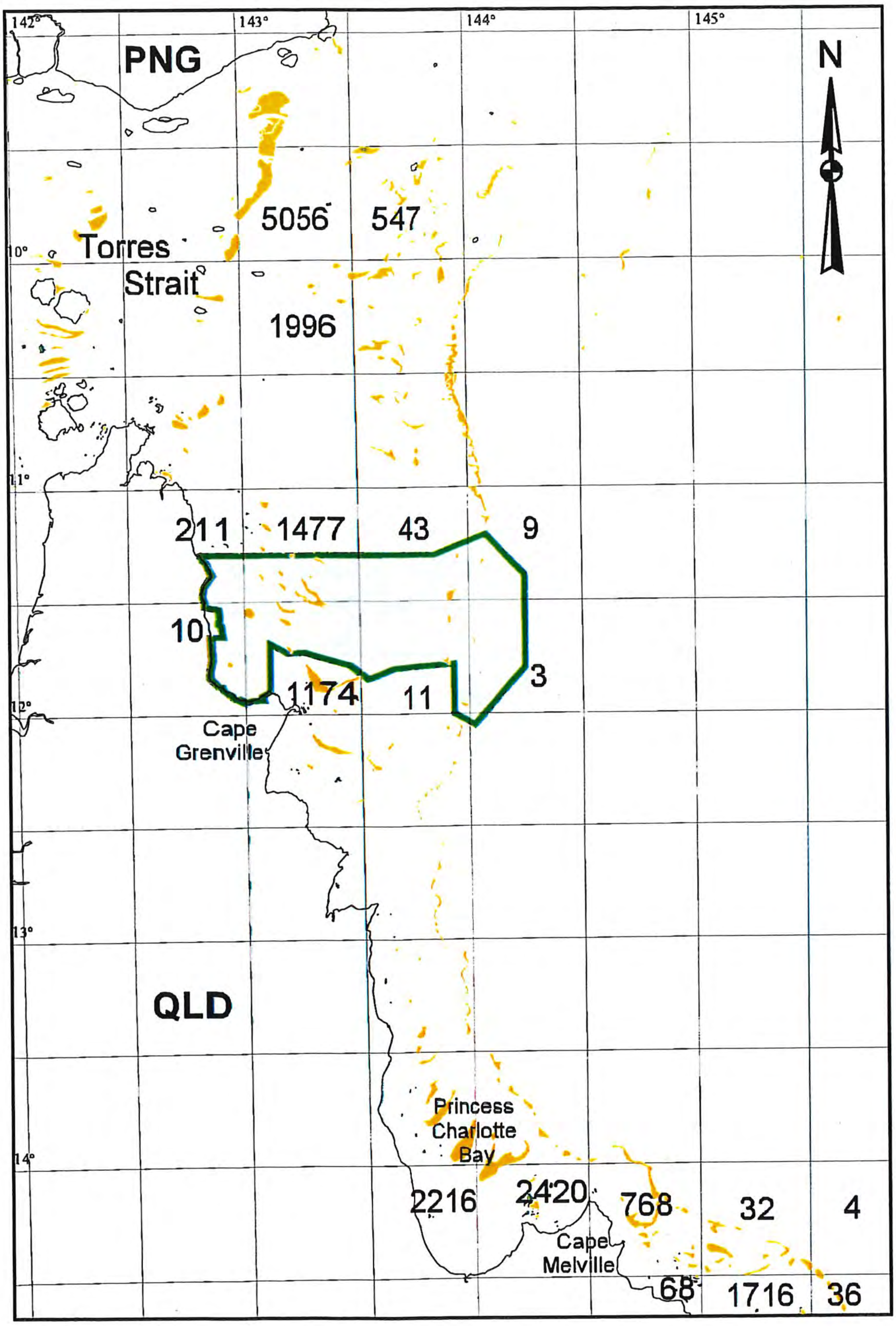


Figure 2.09 (a) Map of the prawn trawl fishing effort (boat days) in the study area, Torres Strait and Princess Charlotte Bay. Grids are 30' x 30'.

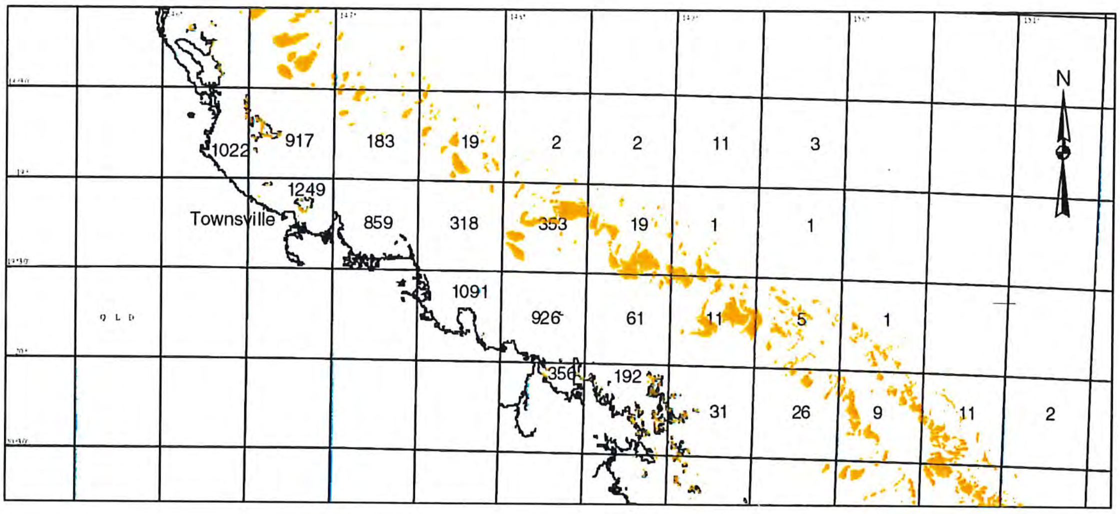


Figure 2.09 **(b)** Map of prawn trawler fishing effort (boat-days) near Townsville (approx 19.3°S) for the 1988-1993 period.

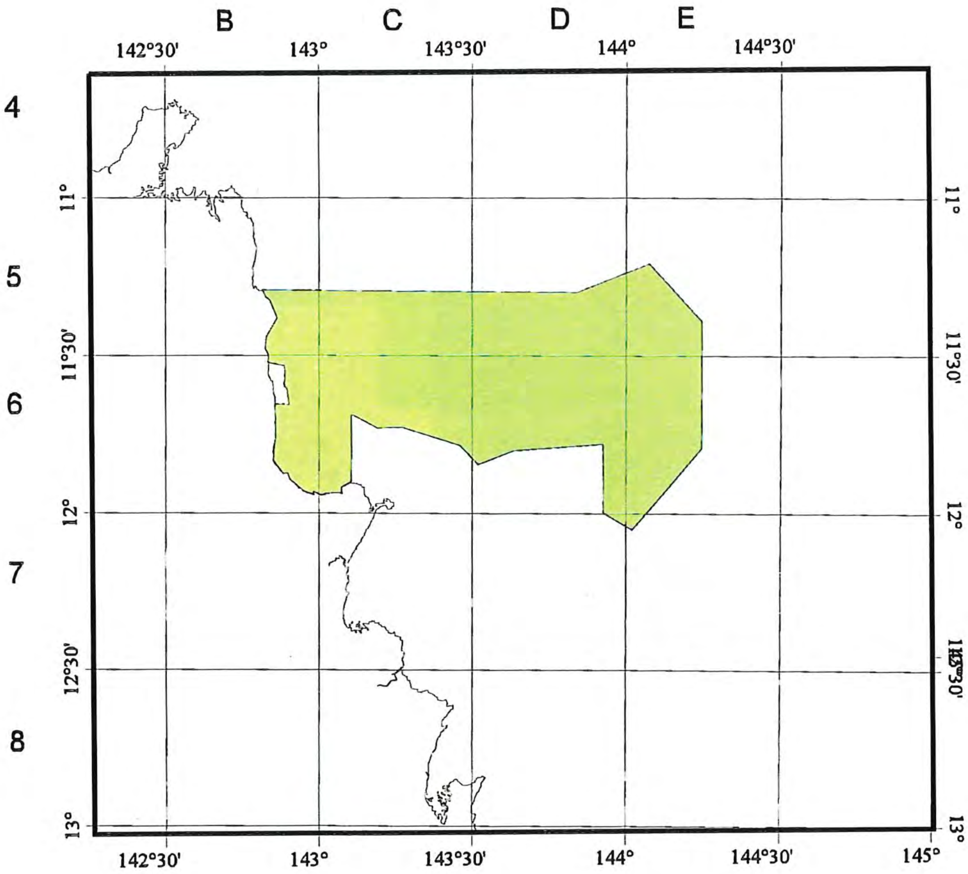


Figure 2.10 Far Northern section of the Great Barrier Reef Marine Park showing QFISH grids (30'x30') and the Green Zone (shaded area). Grids B5, B6, C5, C6, D5, D6, E5 and E6 overlap the Cross-Shelf Closure.

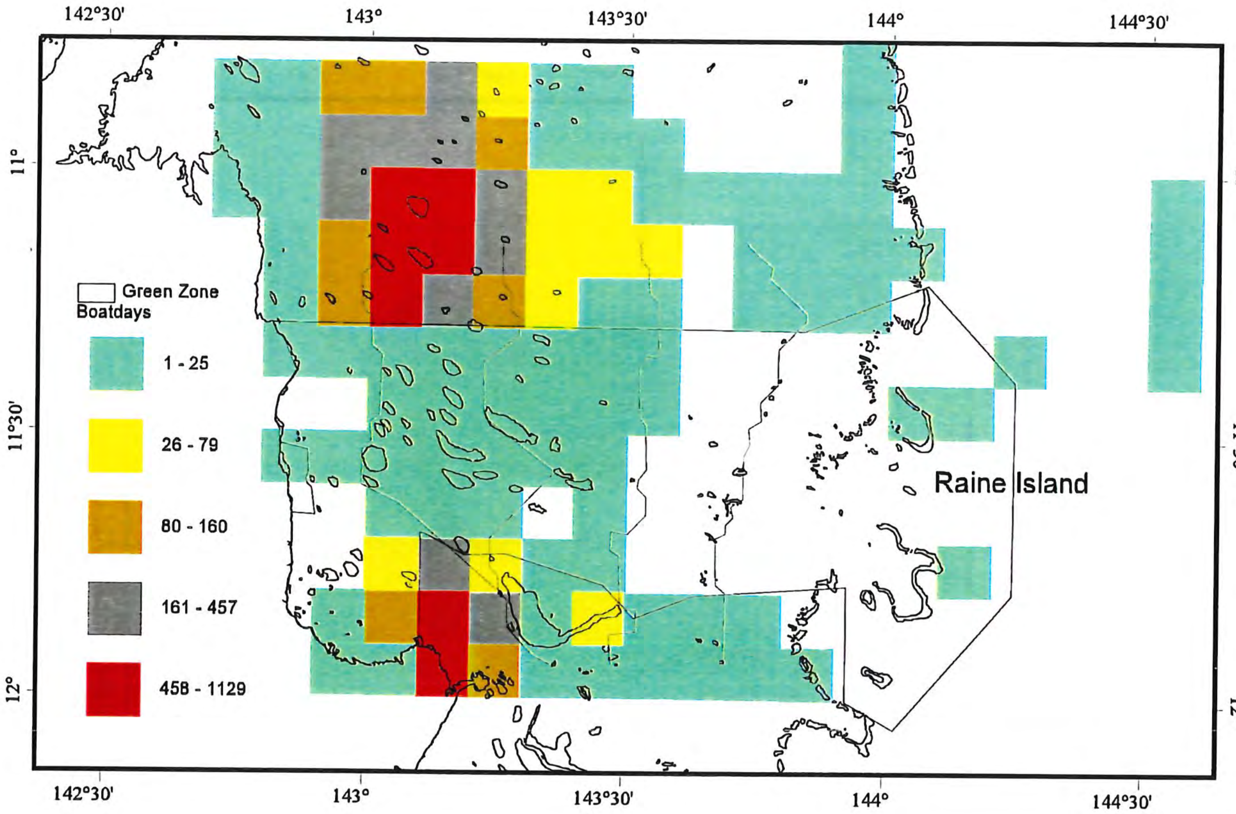


Figure 2.11 Summary map of the geographic distribution of the prawn trawl catch/effort within the study site of the Far Northern Section of the Great Barrier Reef. Taken from the 1992-97 QFISH logbook database. Summary data based on 6′x6′ grids.

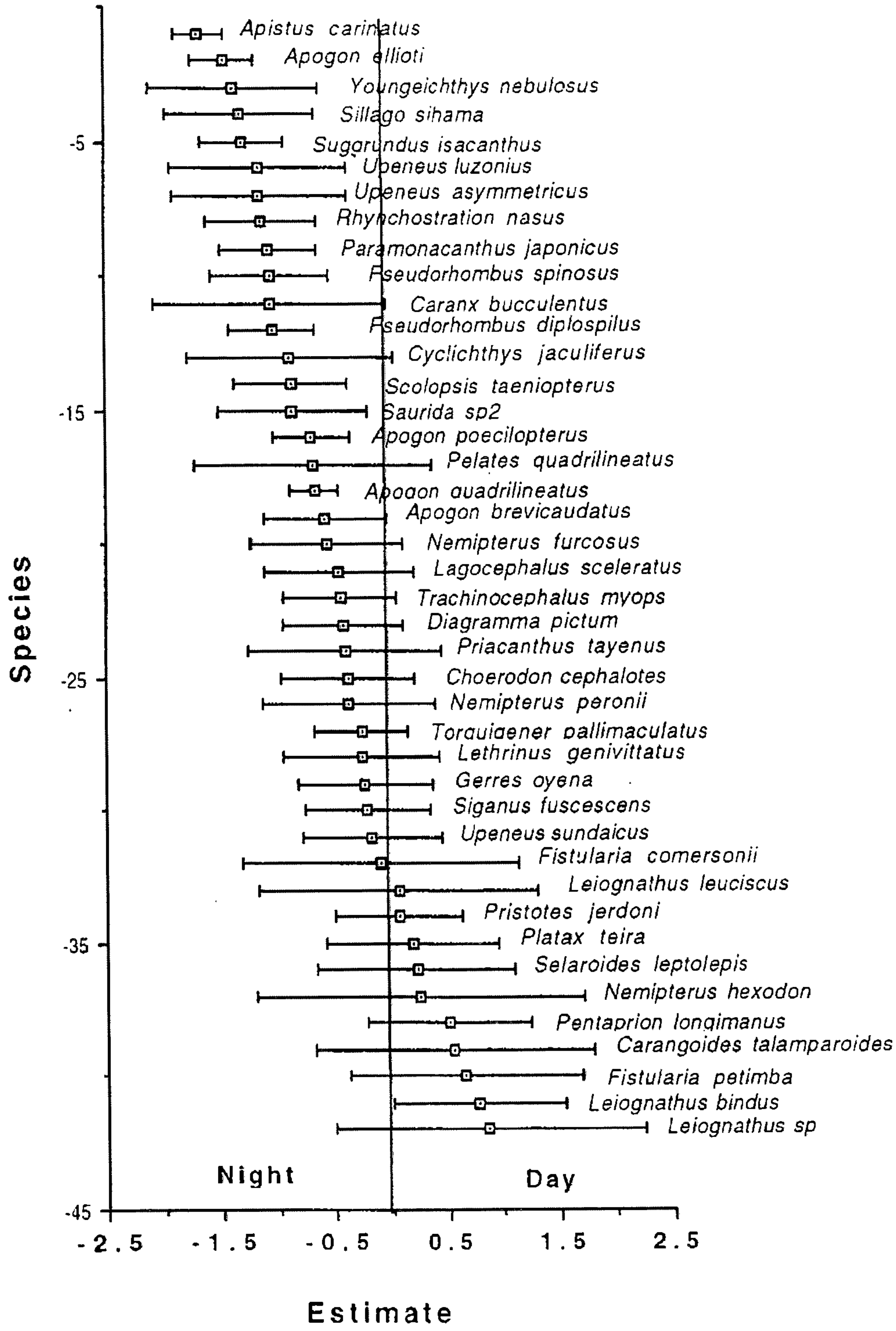


Figure 2.12 A plot of the average diel catch rate of fish species caught at over six stations by a Frank and Bryce demersal fish trawl in the study site of the Far Northern Section of the Great Barrier Reef. The horizontal bars are the 95% confidence limits (7 < n < 24).

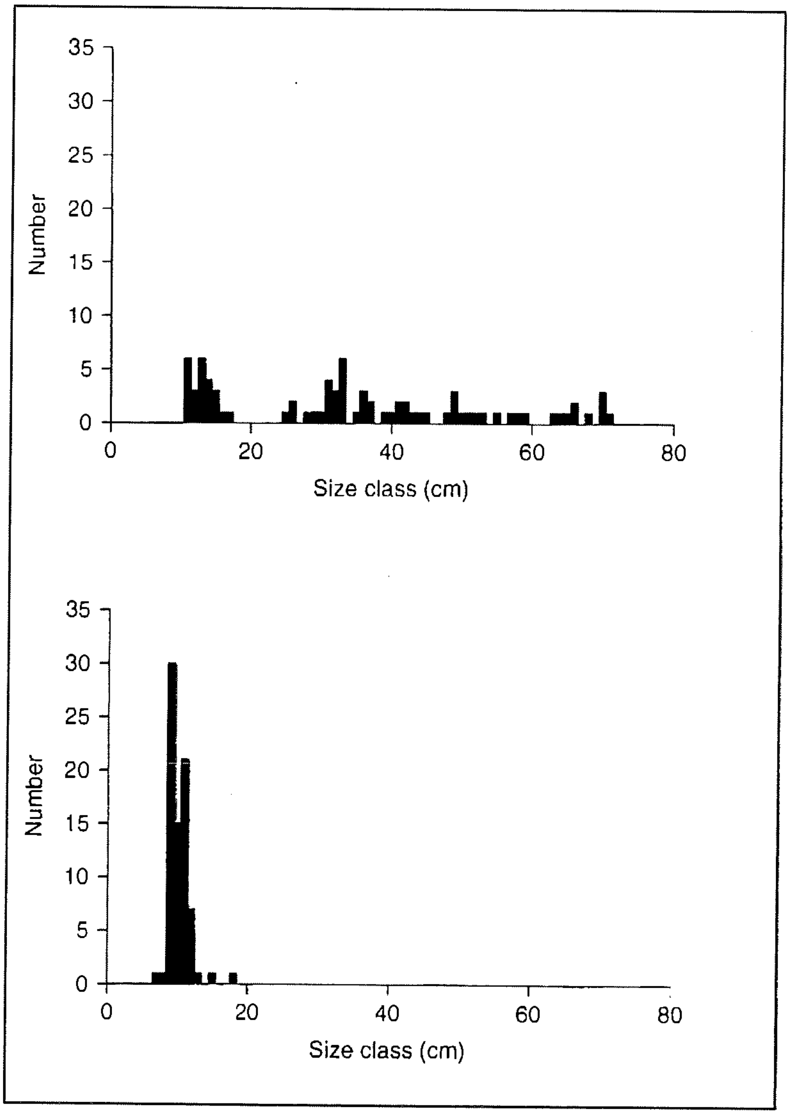


Figure 2.13 Length–frequency distributions for Diagramma pictum caught by a fish trawler (upper) and a prawn trawler (lower) in the study site of the Far Northern Section of the Great Barrier Reef.

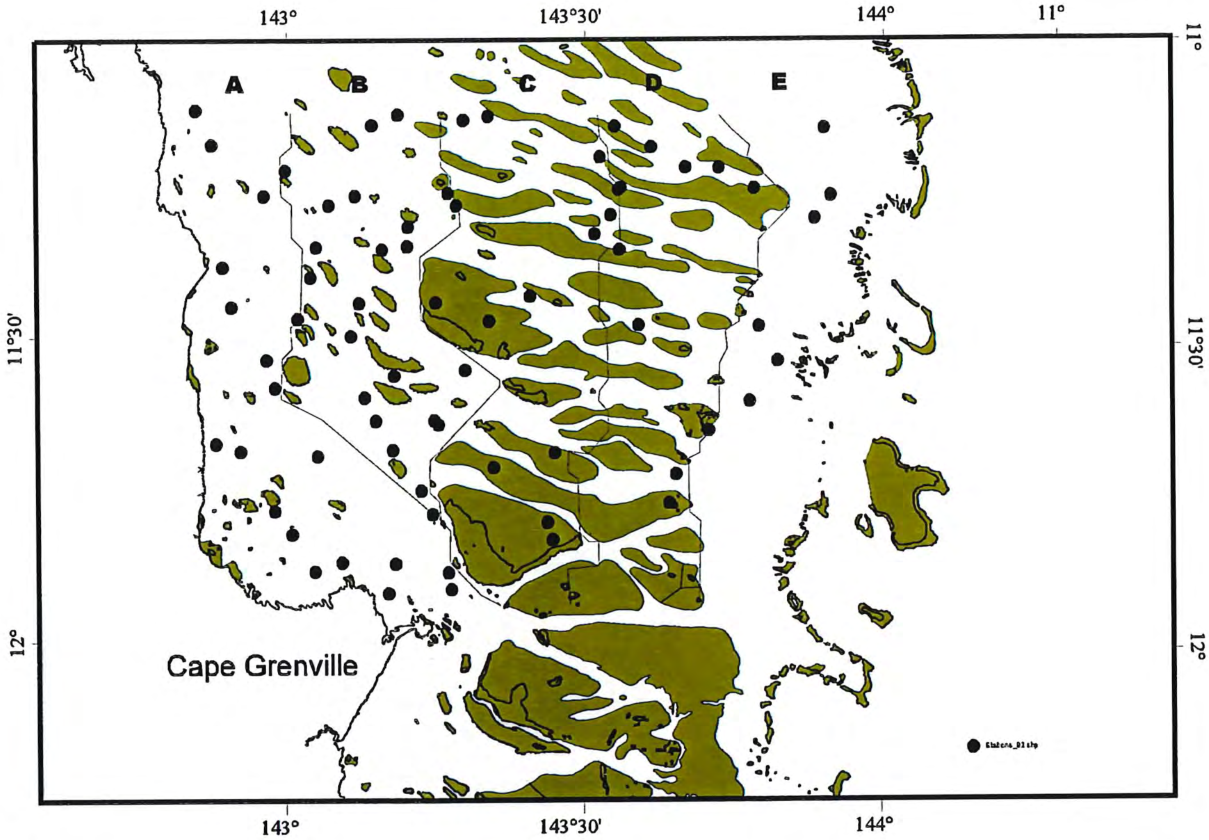


Figure 2.14 (a) Map of the sampling locations for the 1992 survey of the study area in the Far Northern Section of the Great Barrier Reef and the five habitat zones or strata (A-E) defined for the study site.

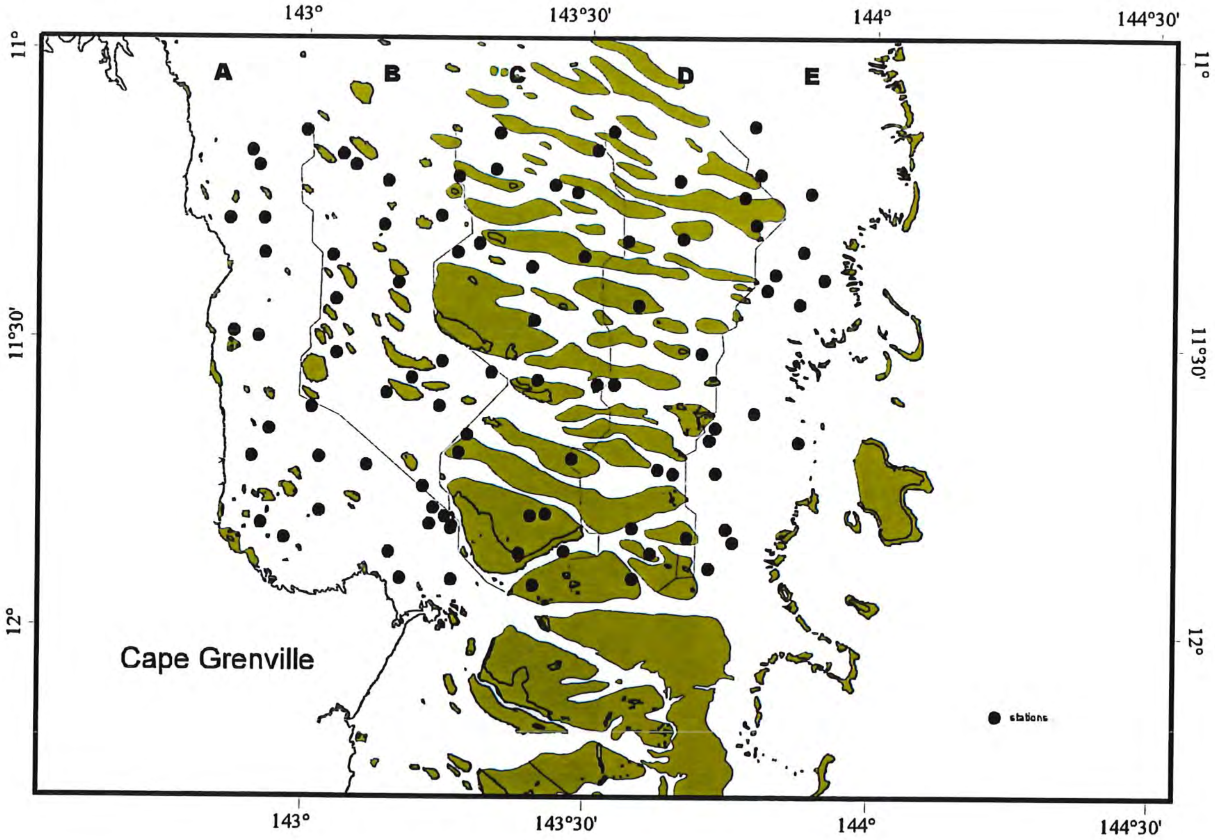


Figure 2.14 (b) Map of the sampling locations for the 1993 survey of the study area in the Far Northern Section of the Great Barrier Reef and the five habitat zones or strata (A-E) defined for the study site.

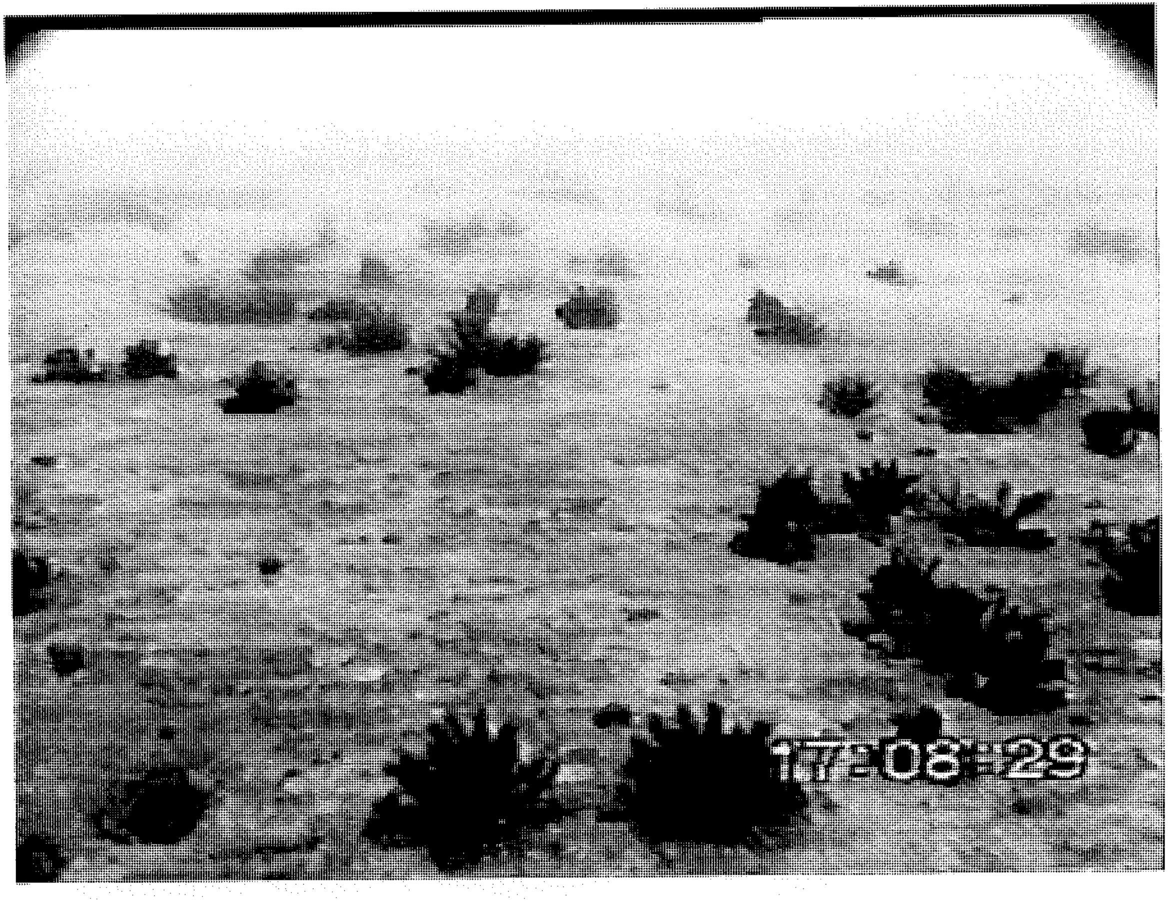


Figure 2.15 (a) Bare substratum – code 1 – in this instance with many crinoids

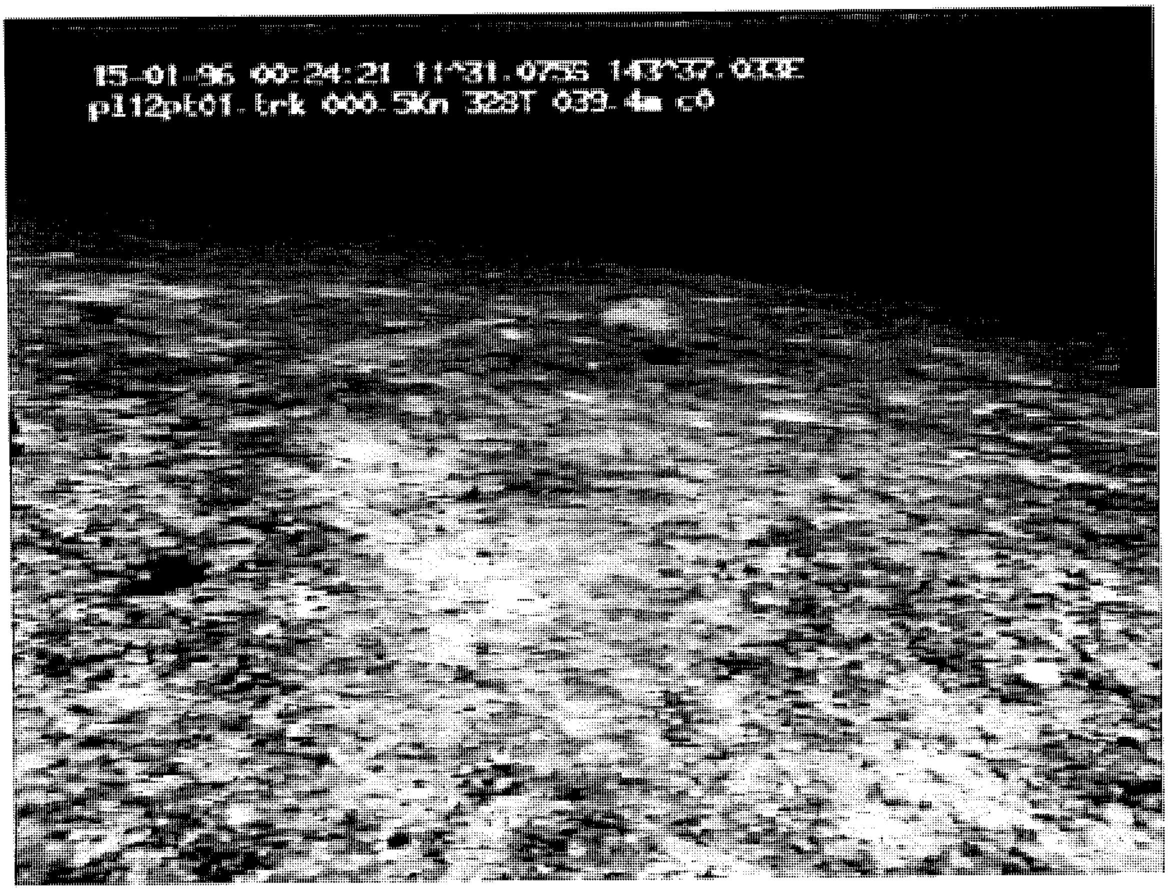


Figure 2.15 (b) Bare substratum with light coating of rubble – code 2.

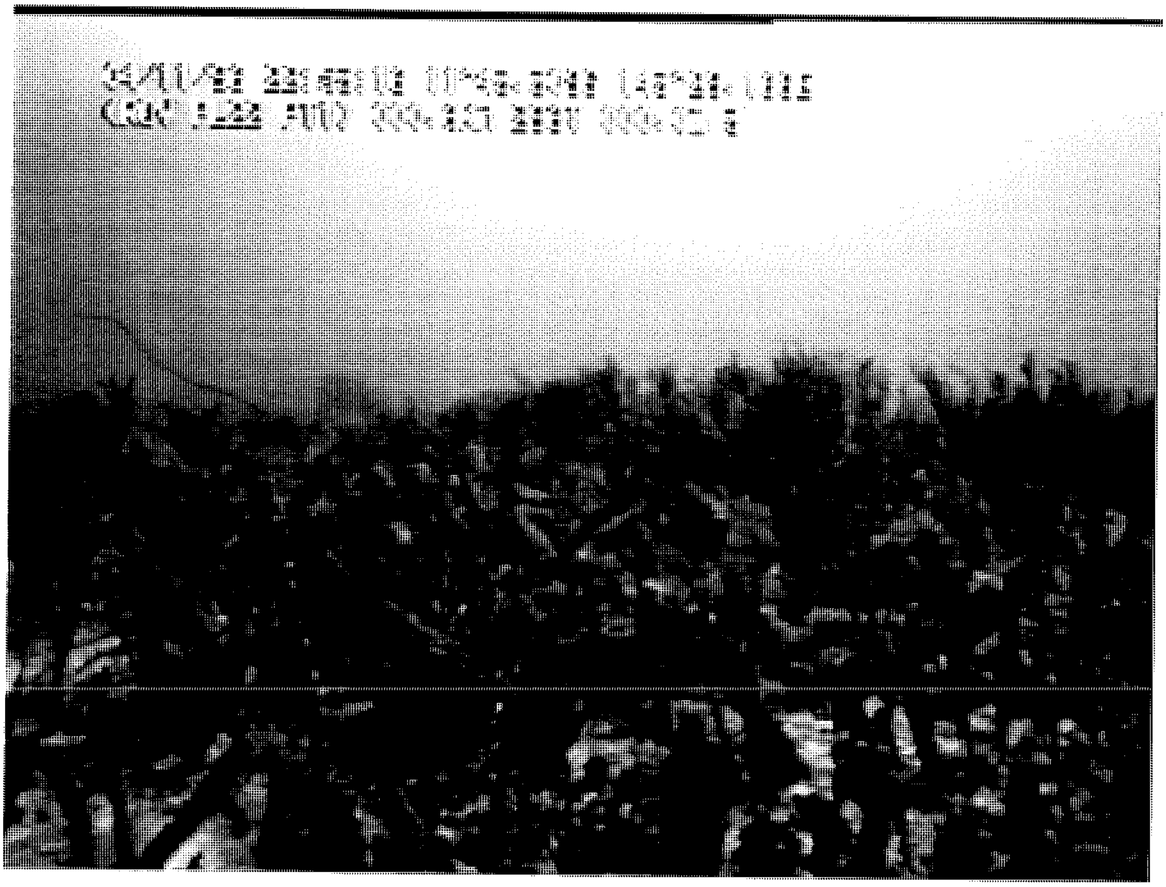


Figure 2.15 (c) Substratum of sand with large patches of algae – code 3 (mostly *Caulerpa* sp).

Figure 2.15 (d) Substratum with beds of *Pinctada* shells in depressions – code 4.

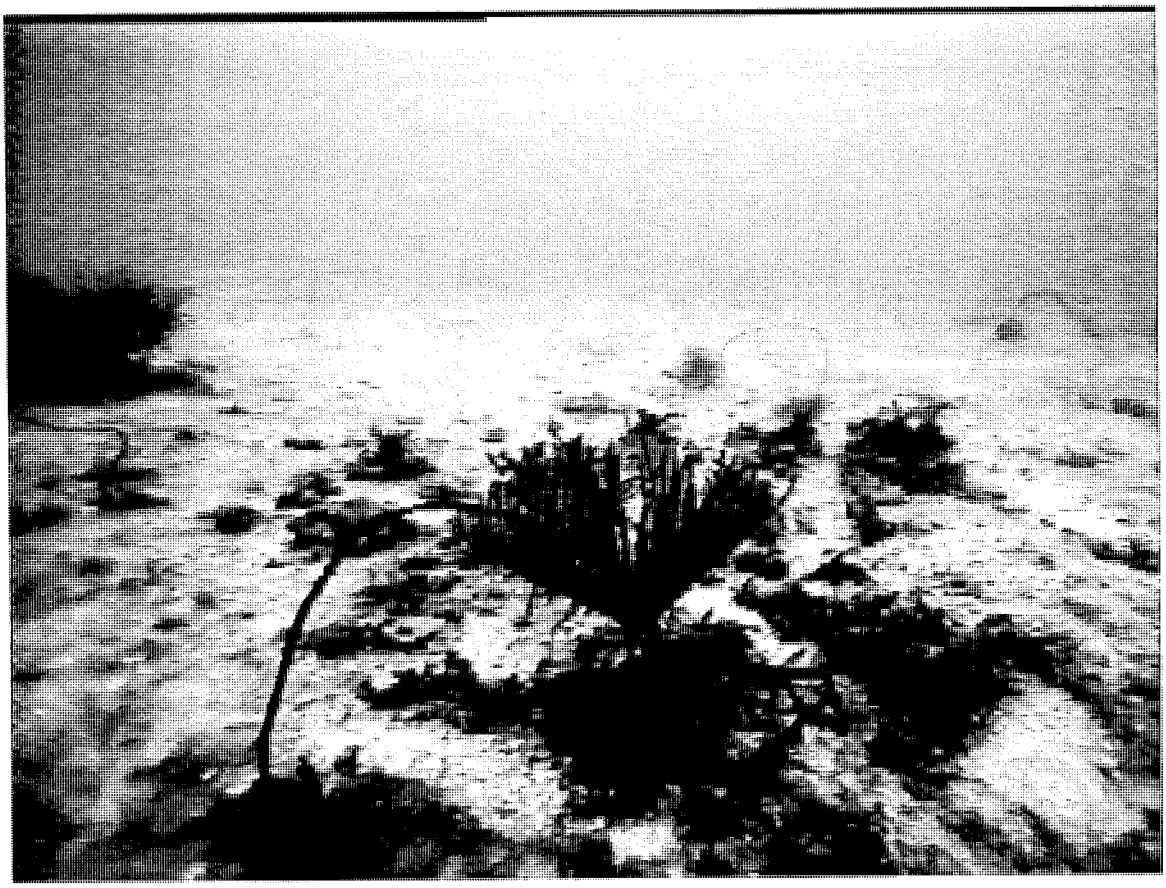


Figure 2.15 (e) Small garden with gorgonians on rubbly substratum – code 5.

Figure 2.15 (f) Larger garden with gorgonians and fan sponges (*Ianthella* sp) – code 6.

Figure 2.15 (g) Garden of gorgonians, sponges and hard corals (often *Turbinaria* sp.) – code 7. The corals have white edges, the fan sponge at the top left is an *Ianthella* sp.

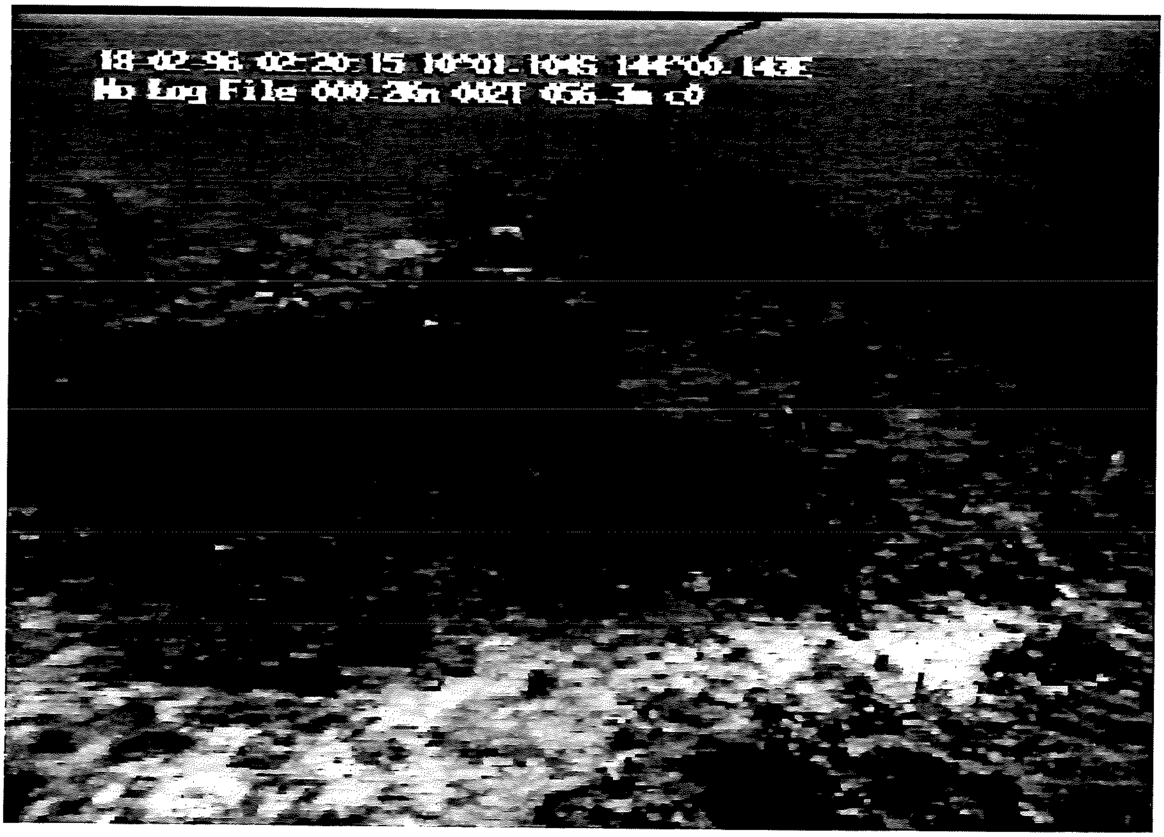


Figure 2.15 (h) Rough ground with a rock ledge – code 8.

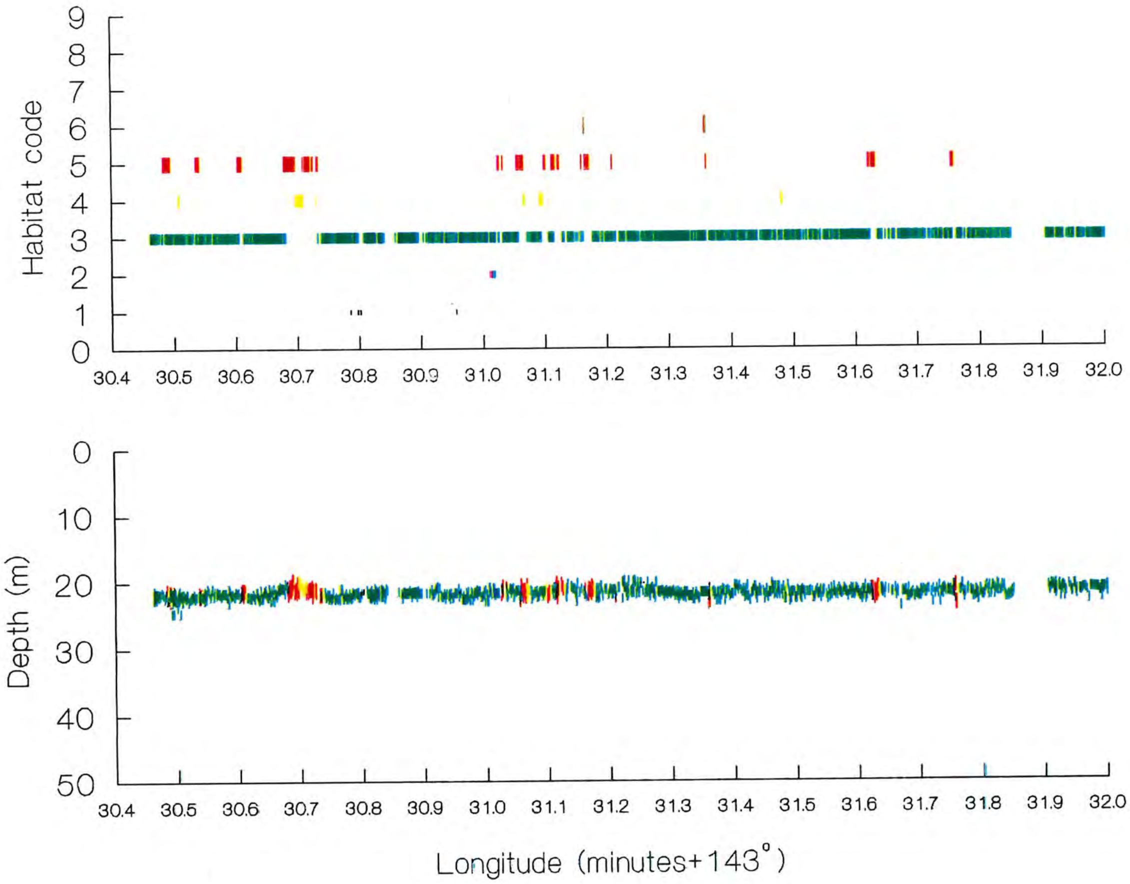


Figure 2.16 (a) Distribution of major benthos types in ~2.8 km long coded video transects along a shallow (~20 m) shoaling seabed in the midshelf of the Green Zone. Codes: 1=silt/sand (black), 2=rubble (blue), 3=algae (green), 4=shell beds (yellow), 5=patches of seawhips and gorgonians (red), 6=5+sponges (brown), 7=6+hard corals, 8=rocks, 9=reef. The multiple scales of patchiness of benthos are clearly apparent. Increments on the horizontal axis are equal to about 181 m. (Exploded view - upper graph, normal view - lower graph).

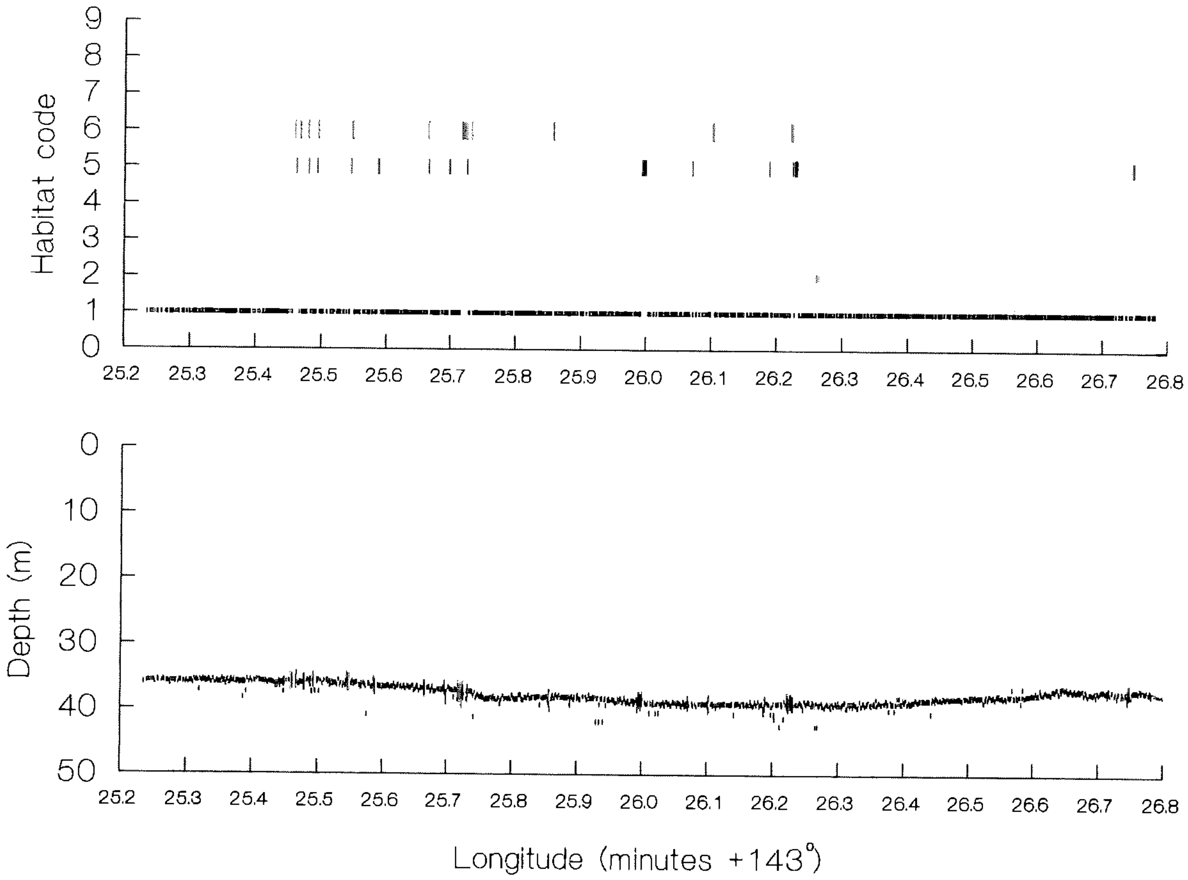


Figure 2.16 (b) Distribution of major benthos types in ~2.8 km long coded video transects along a deep (~35 m) seabed in the midshelf of the Green Zone. 1=silt/sand (black), 2=rubble (blue), 3=algae (green), 4=shell beds (yellow), 5=patches of seawhips and gorgonians (red), 6=5+sponges (brown), 7=6+hard corals, 8=rocks, 9=reef. The multiple scales of patchiness of benthos are clearly apparent. Increments on the horizontal axis are equal to about 181 m. (Exploded view - upper graph, normal view - lower graph).

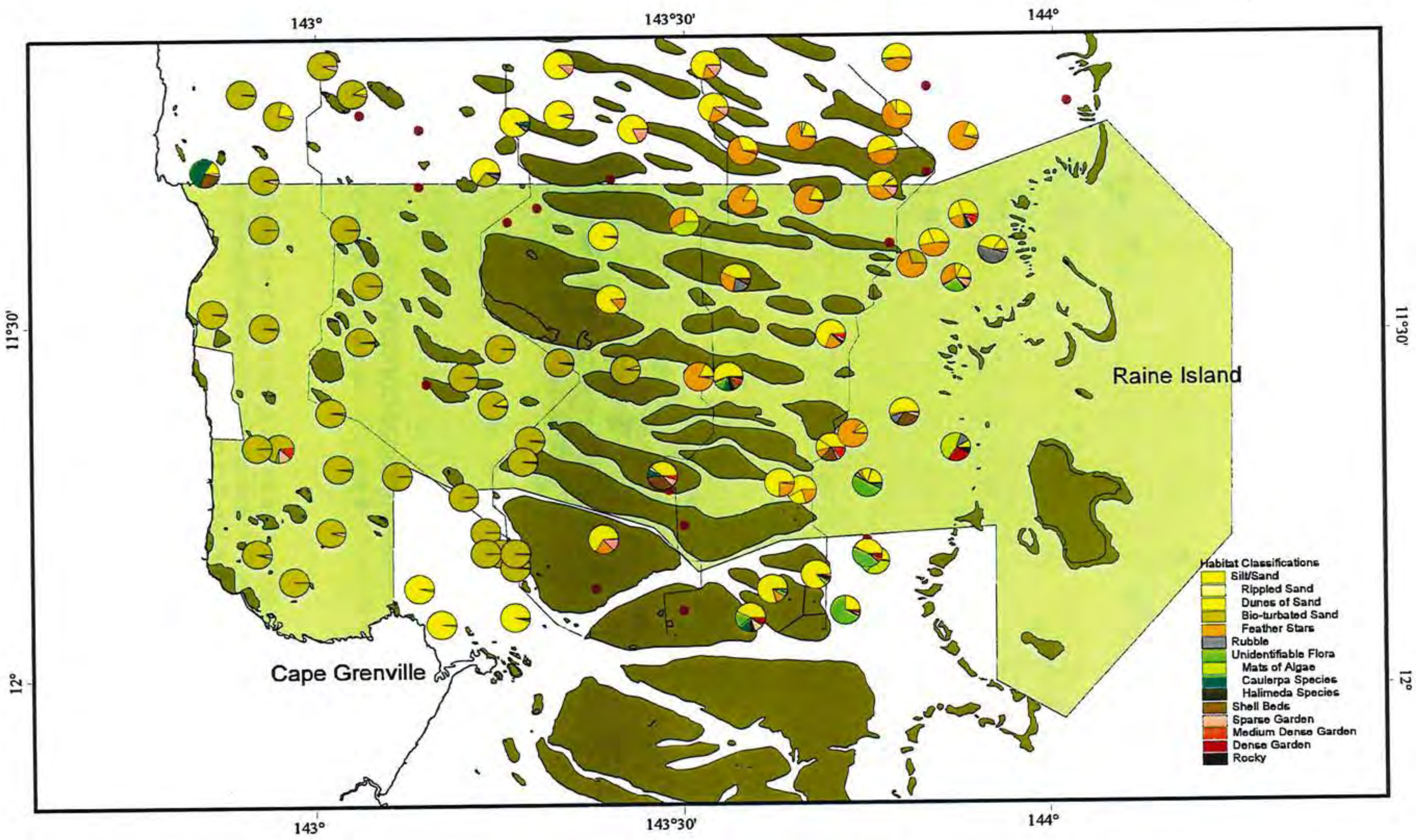


Figure 2.16 **(c)** Relative proportions of habitat types at the 1993 sites in the study area derived from towed video sled observations. Inshore (strata A and B) the habitat was mostly bioturbated sand. The offshore sites were predominantly sandy with increasing complexity of habitat in strata D and E. The small brown circles are sites at which video data was collected but could not be analysed because of poor visibility or because the slec could not be towed, and so diver held video camera records were made.

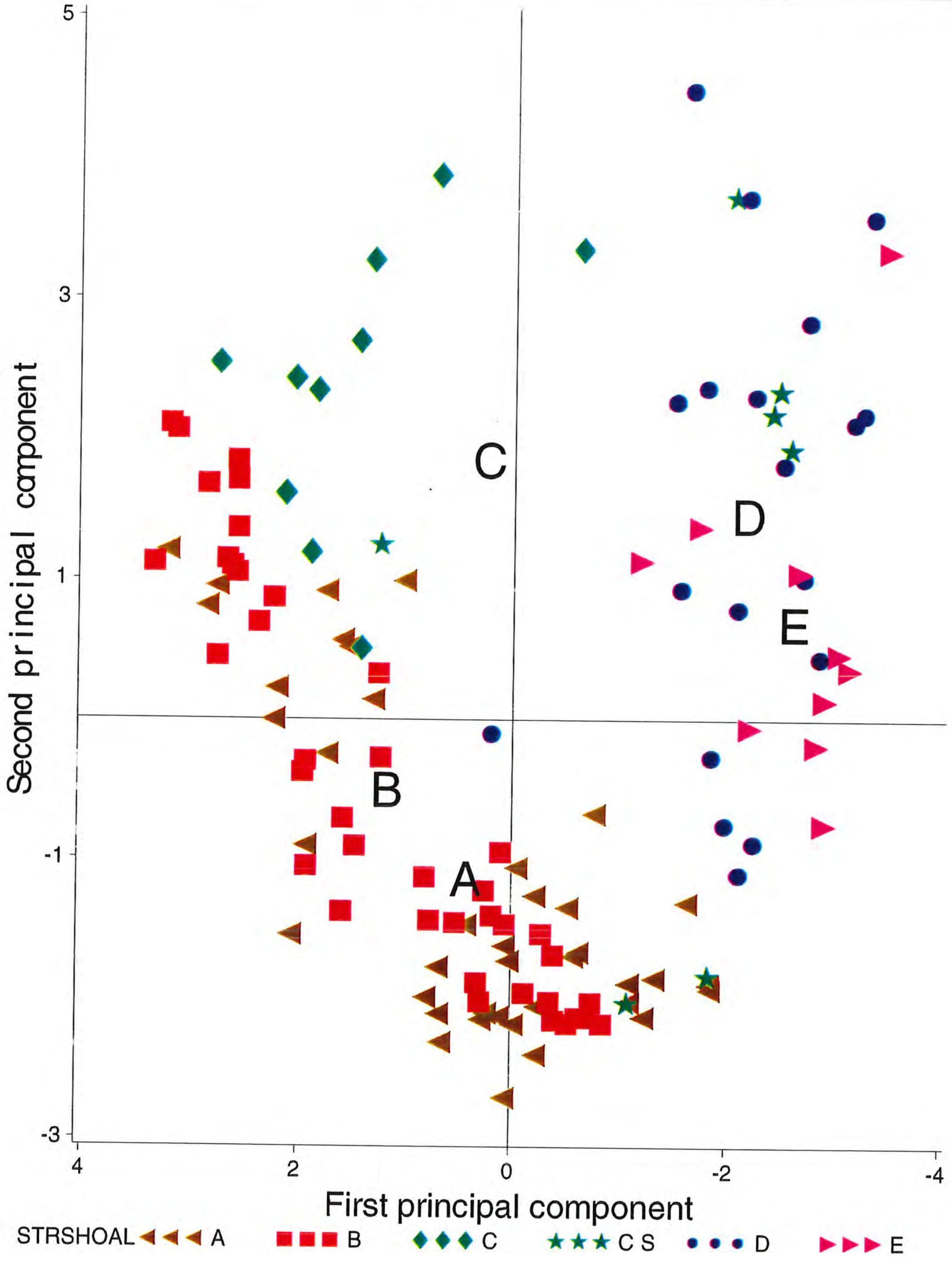


Figure 2.17 Plot of the principal component scores for stations from the prawn trawl tows within strata in the study area of the Far Northern Section of the Great Barrier Reef. (1992-1993).The letters show the mean position for each stratum

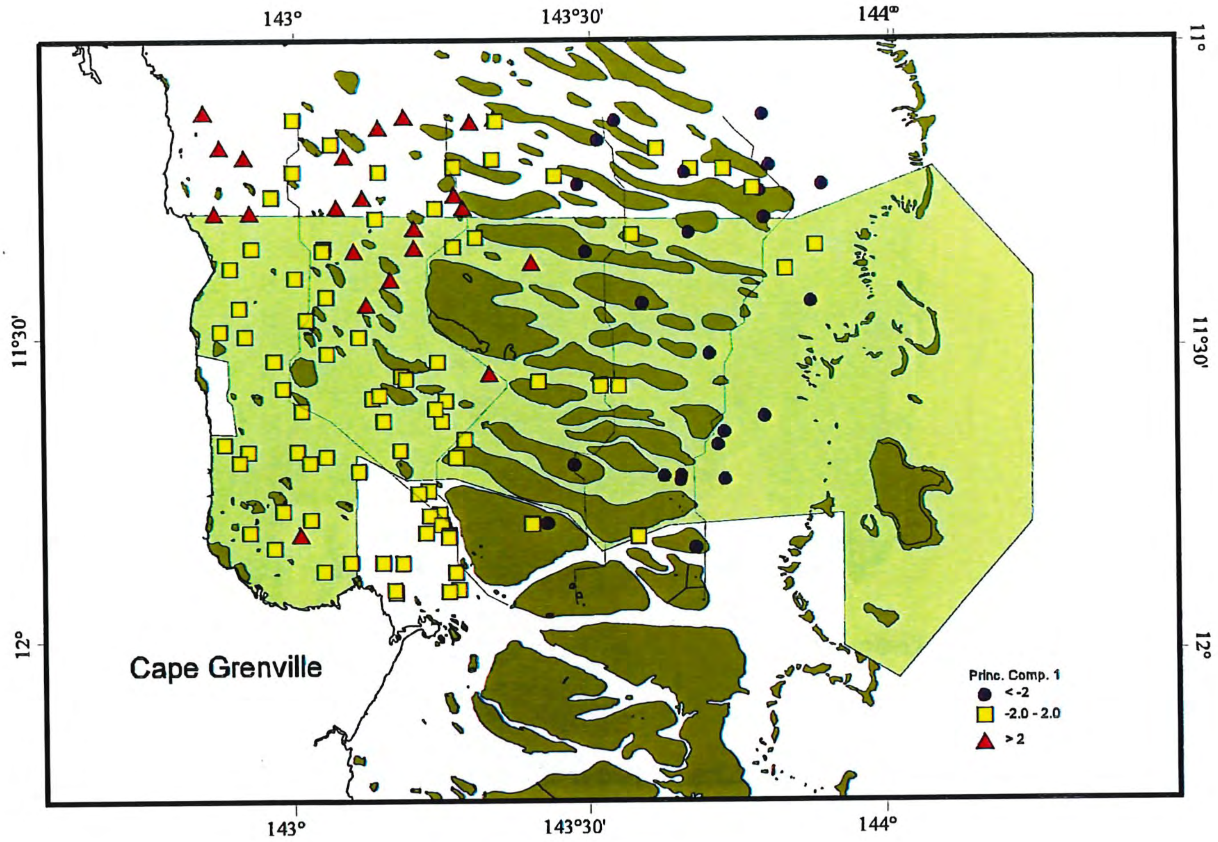


Figure 2.18 Species community profile according to the first principal component for the prawn species from the prawn trawl overlaid on a map of the study area in the Far Northern Section of the Great Barrier Reef. (1992-1993).

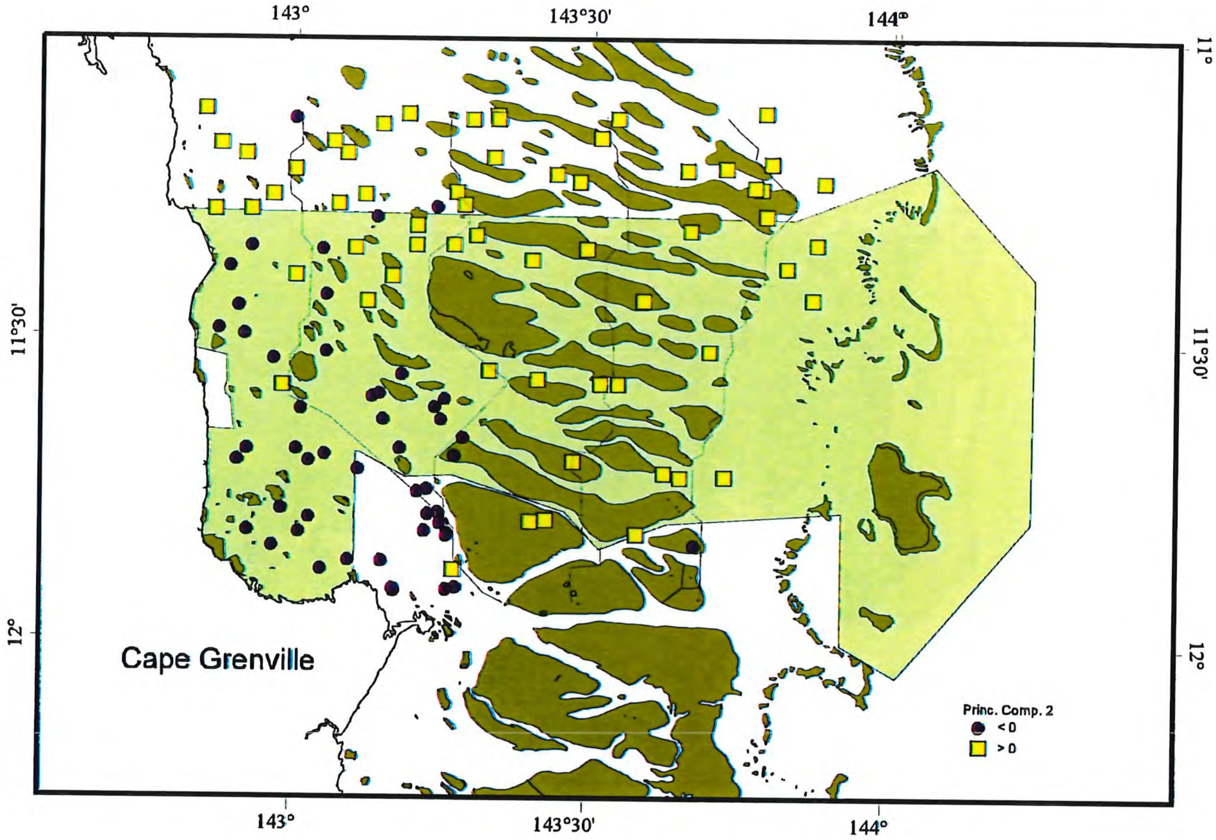


Figure 2.19 Species community profile according to the second principal component for the prawn species from the prawn trawl overlaid on a map of the study area in the Far Northern Section of the Great Barrier Reef. (1992-1993).

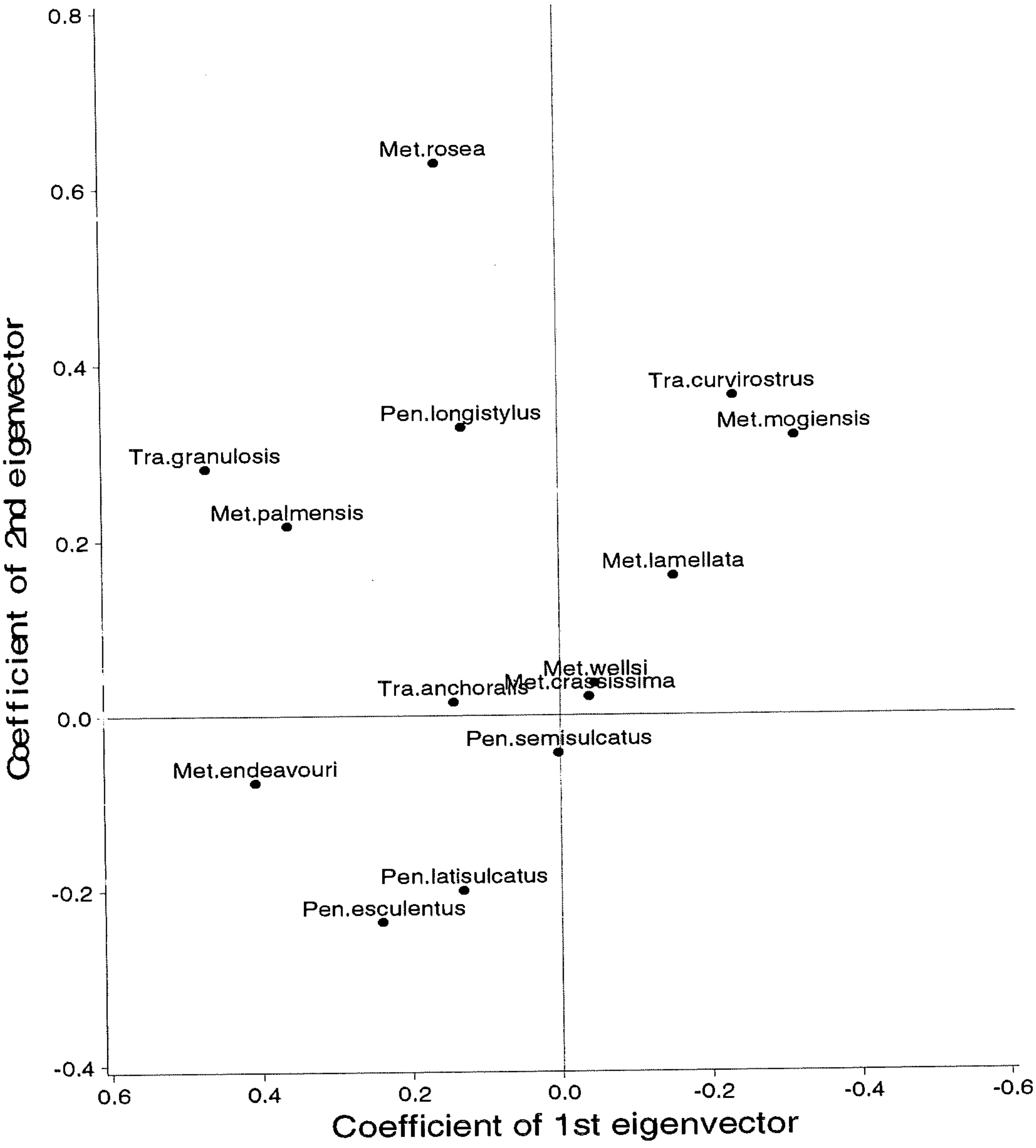


Figure 2.20 Eigenvector coefficients of prawn species from prawn trawl tows in the study area of the Far Northern Section of the Great Barrier Reef (1992-1993) with outliers identified.

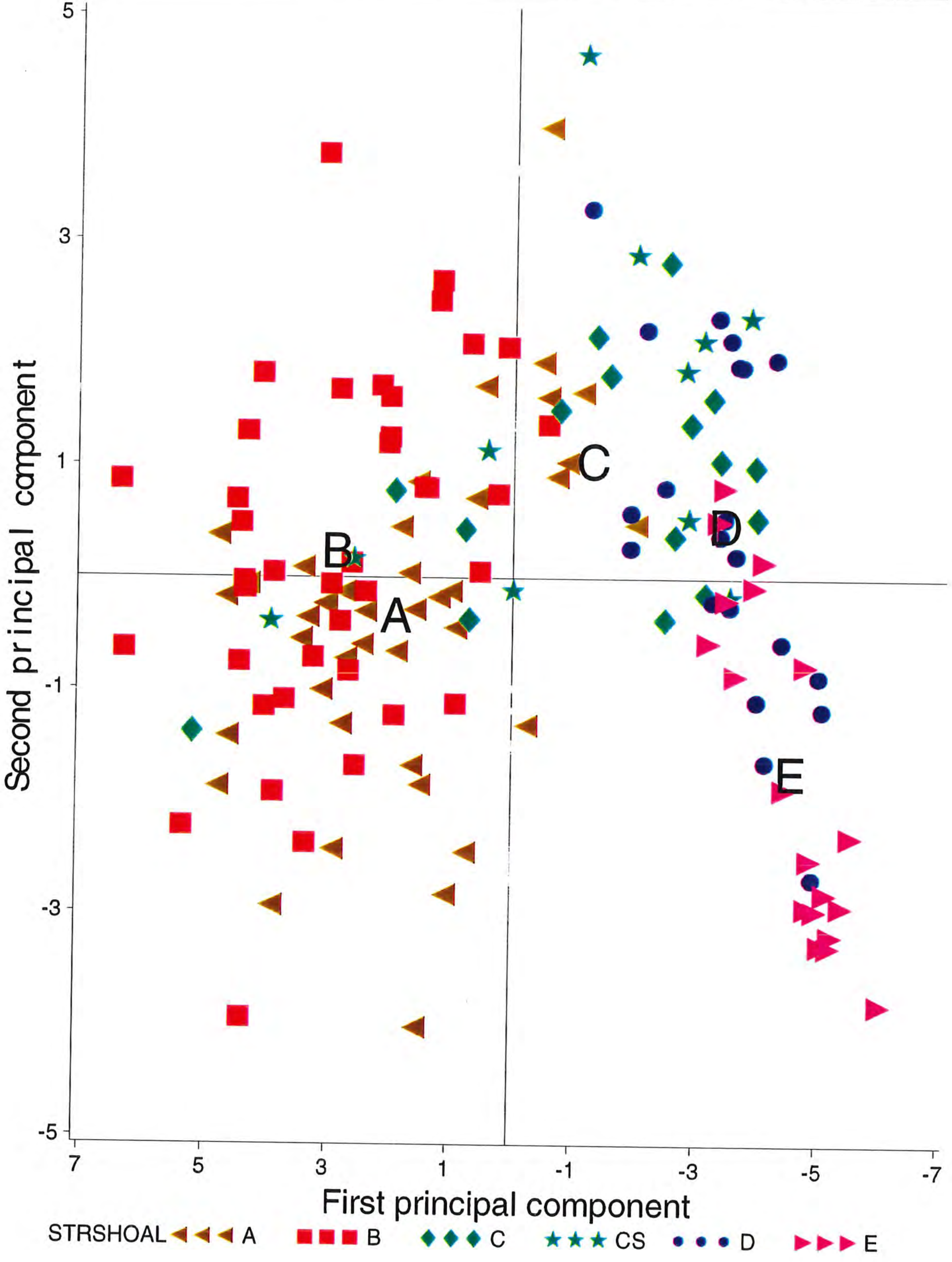


Figure 2.21 Plot of the principal component scores for bycatch stations from prawn trawls within strata in the study area of the Far Northern Section of the Great Barrier Reef (1992-1993). The letters show the mean position for each stratum

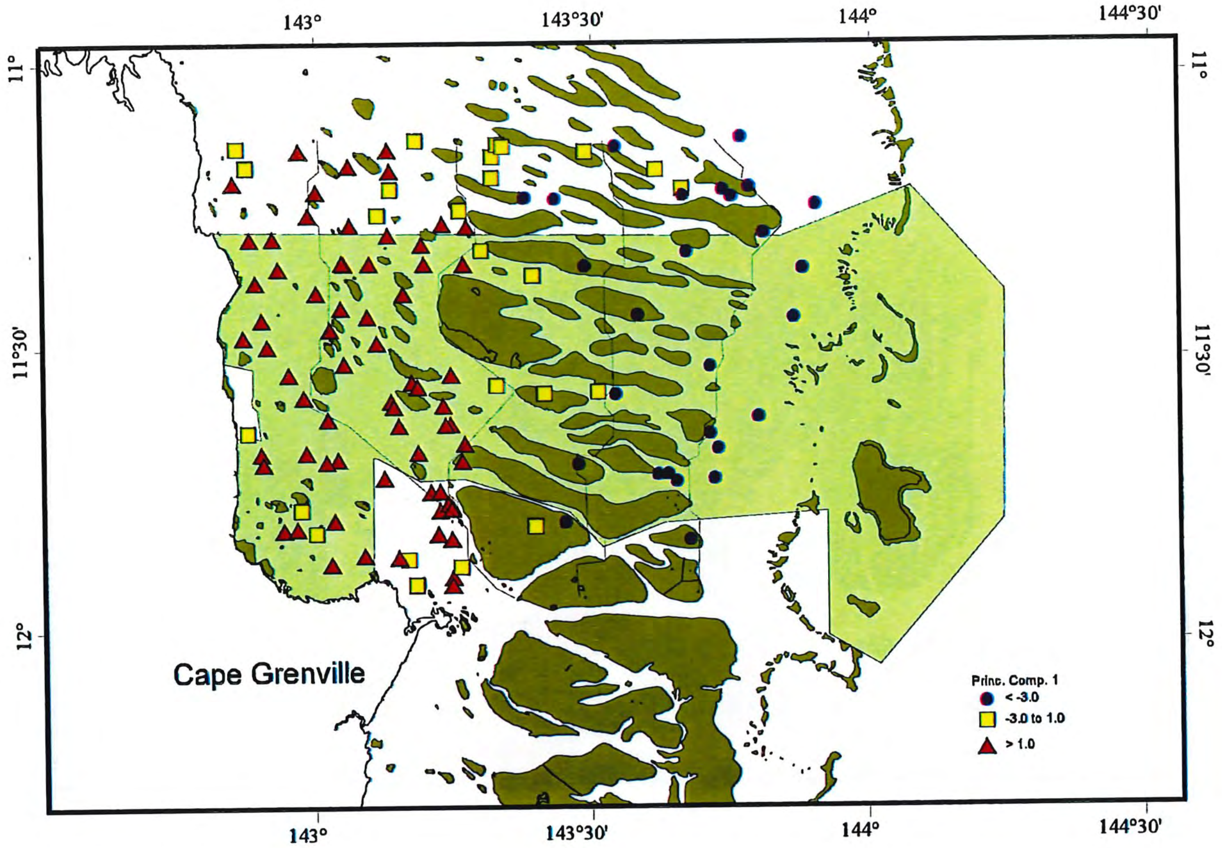


Figure 2.22 Species community profile according to the first principal component for bycatch species from the prawn trawl tows overlaid on a map of the study area (1992-1993).

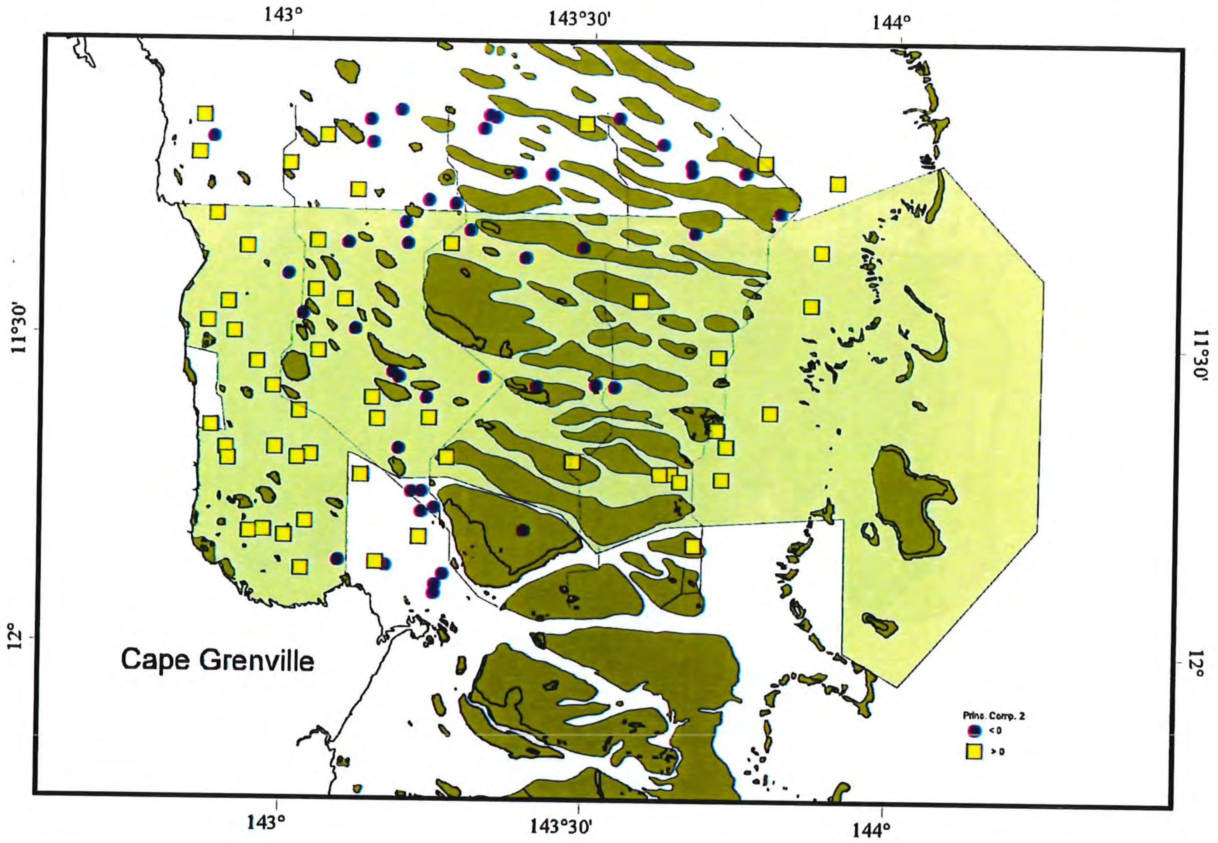


Figure 2.23 Species community profile according to the second principal component for bycatch from prawn trawl tows in the study area of the Far Northern Section of the Great Barrier Reef (1992-1993).

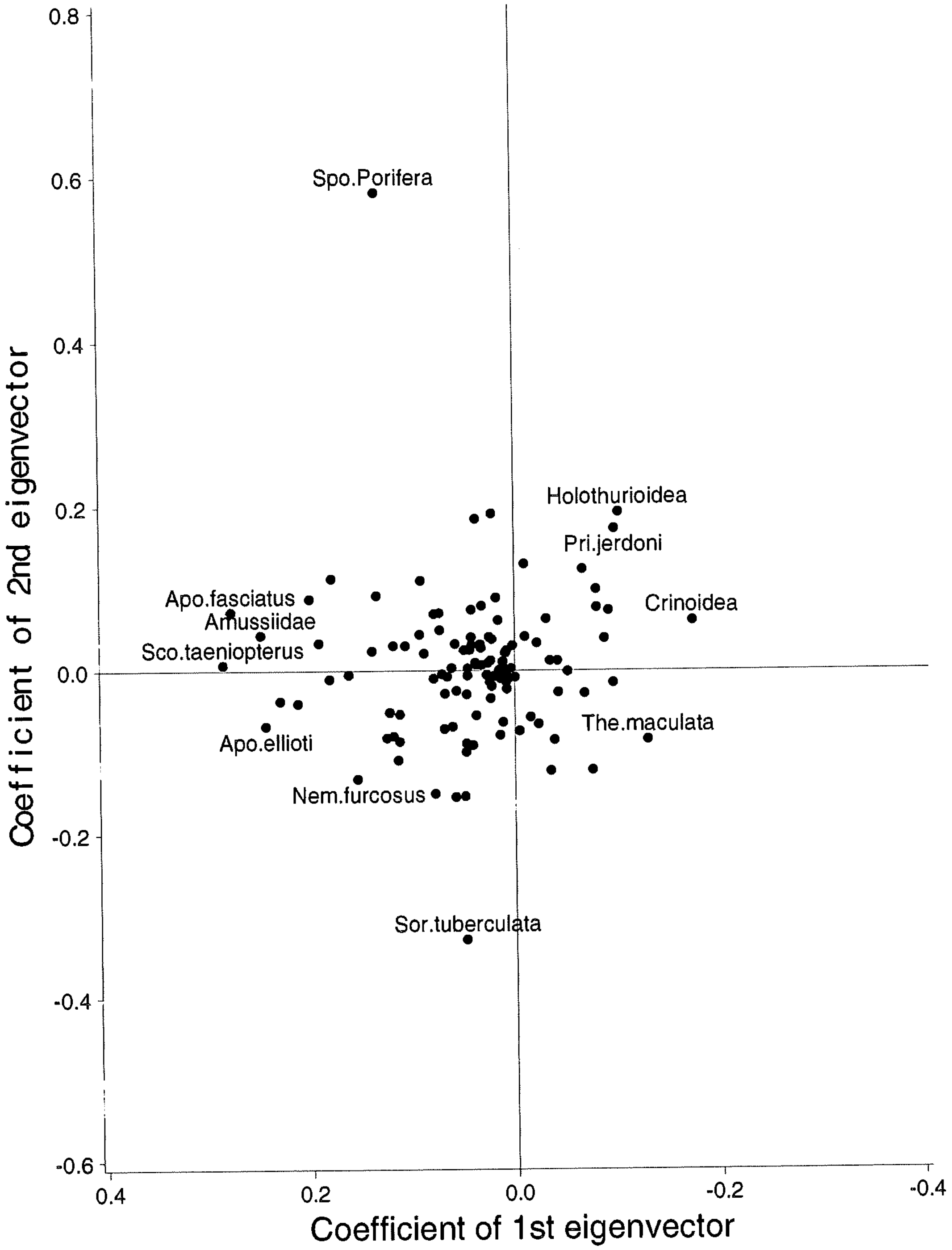


Figure 2.24 Eigenvector coefficients of bycatch species/taxa from prawn trawler tows in the study area of the Far Northern Section of the Great Barrier Reef (1992-1993) with outliers identified.

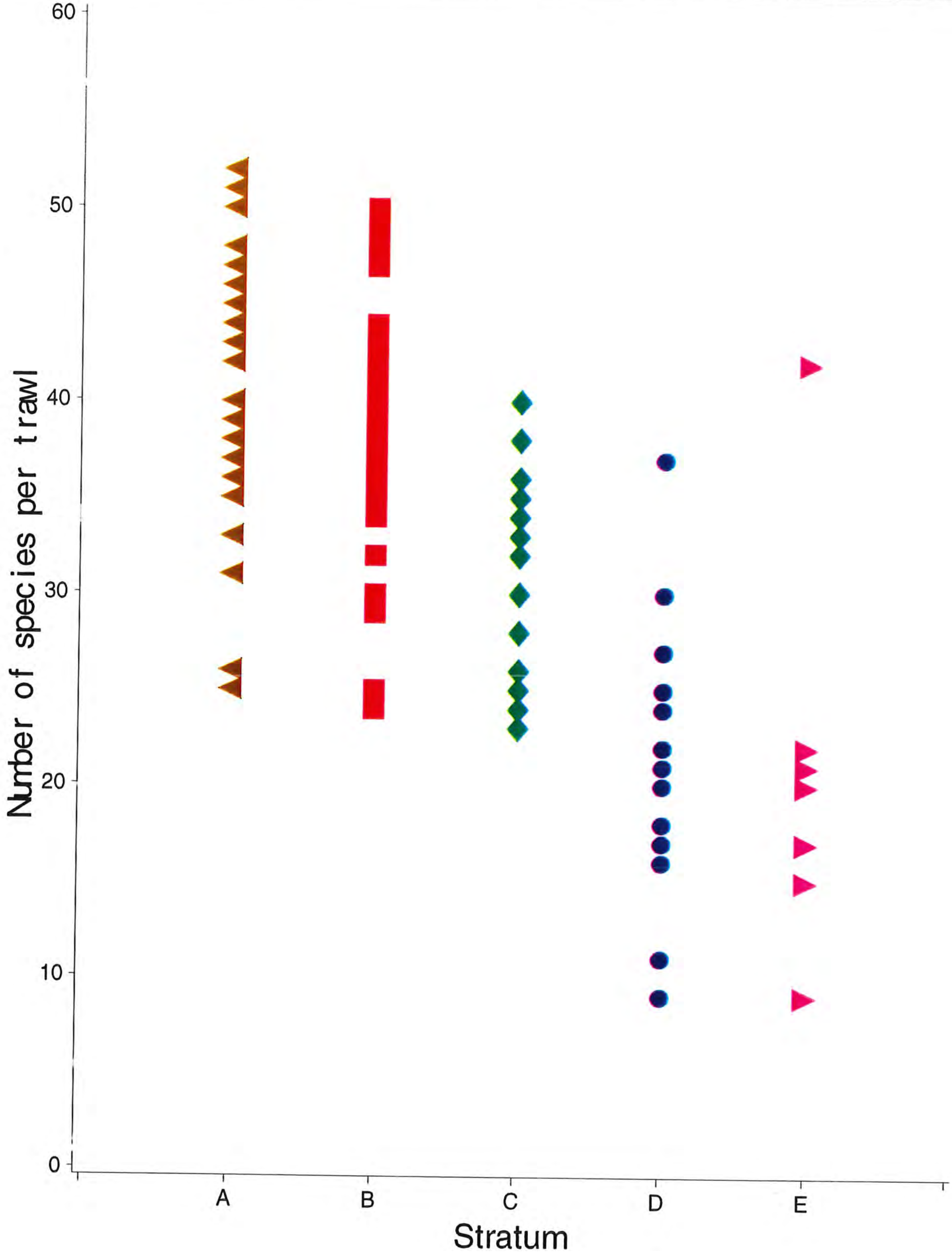


Figure 2.25 Number of species of fish per prawn trawl tow for bycatch within each stratum in the study area of the Far Northern Section of the Great Barrier Reef (1992-1993).

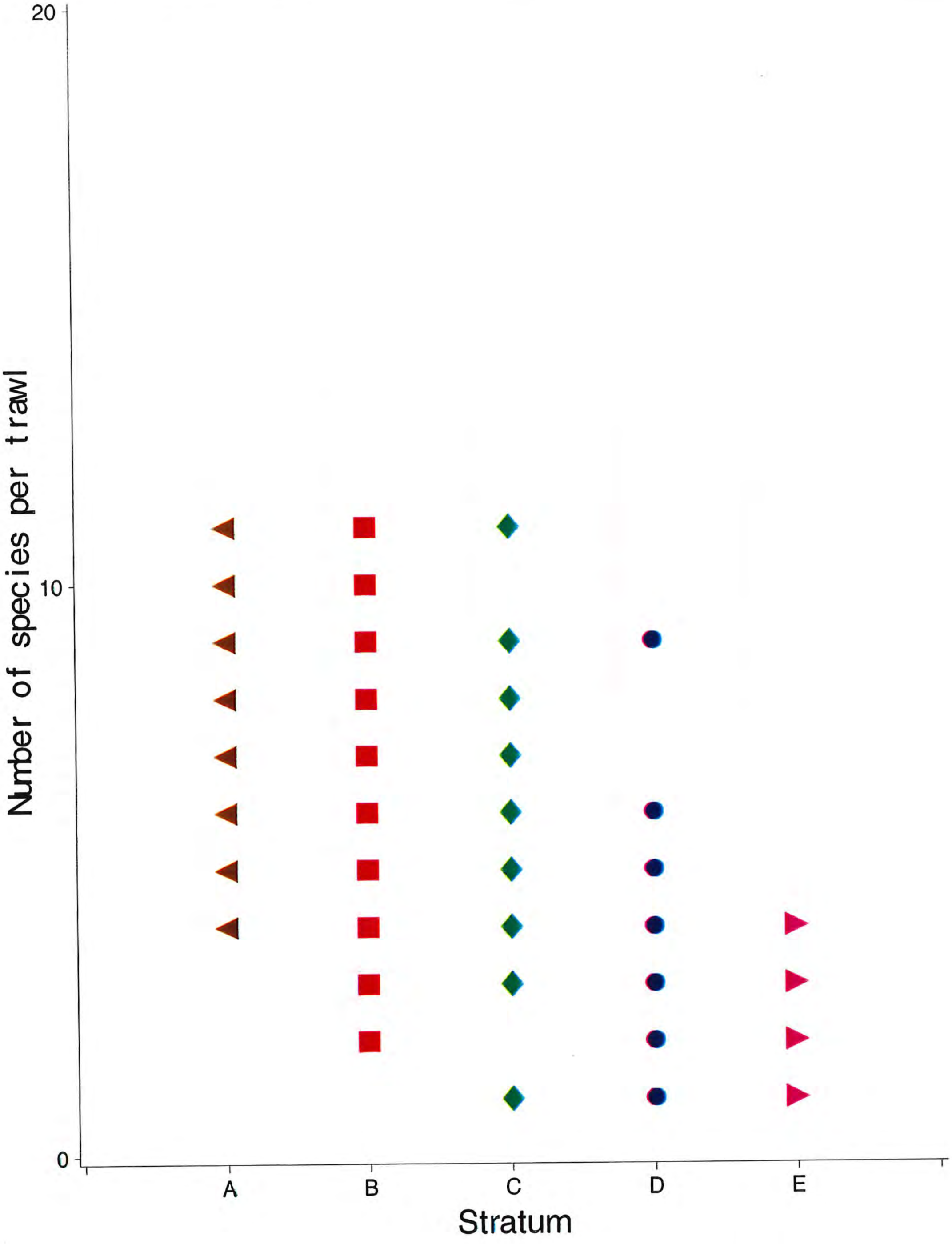


Figure 2.26 Number of species of crustaceans per prawn trawl tow for bycatch within each stratum in the study area of the Far Northern Section of the Great Barrier Reef (1992-1993).

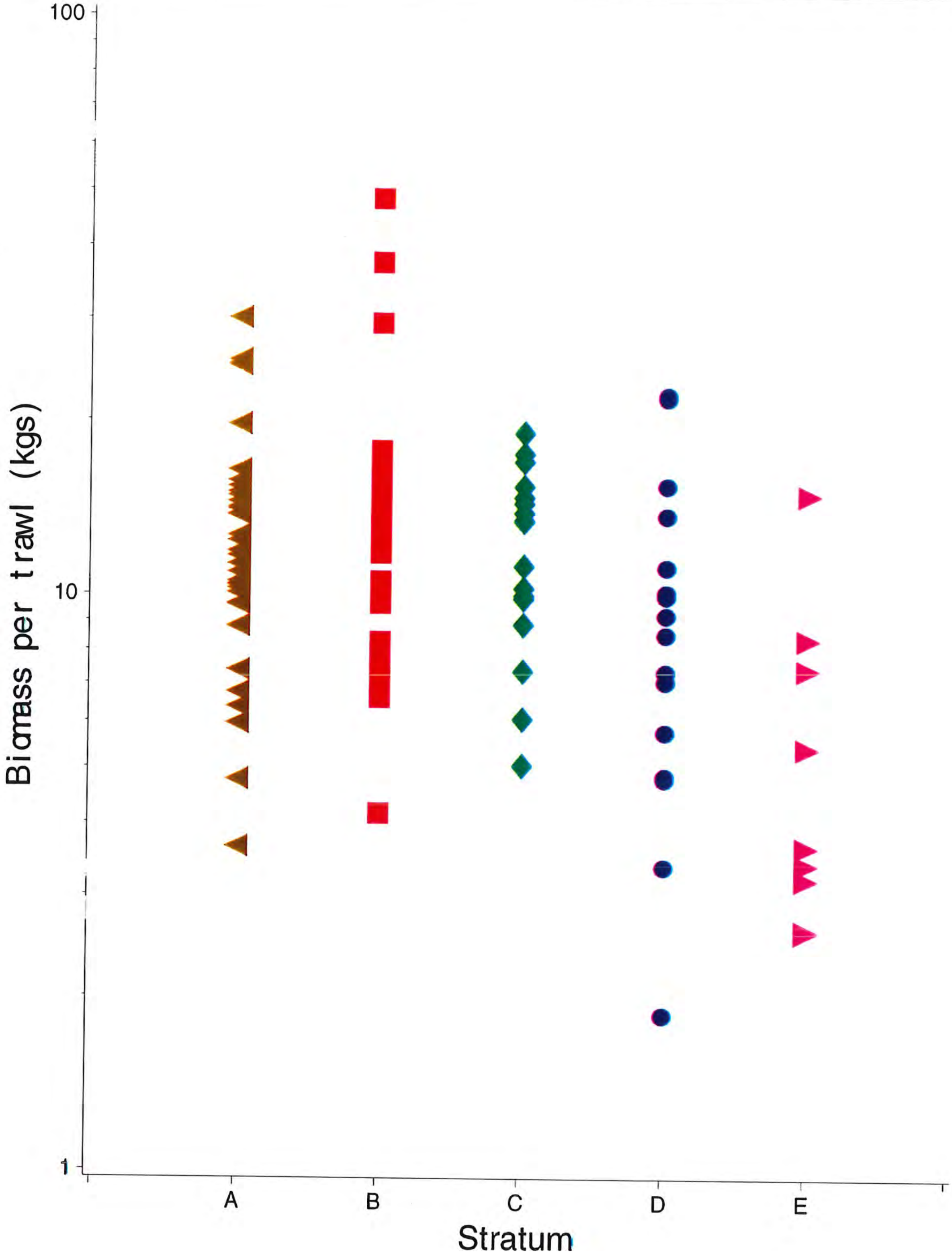


Figure 2.27 Total weight of species of fish per prawn trawl tow for bycatch within each stratum in the study area of the Far Northern Section of the Great Barrier Reef (1992-1993).

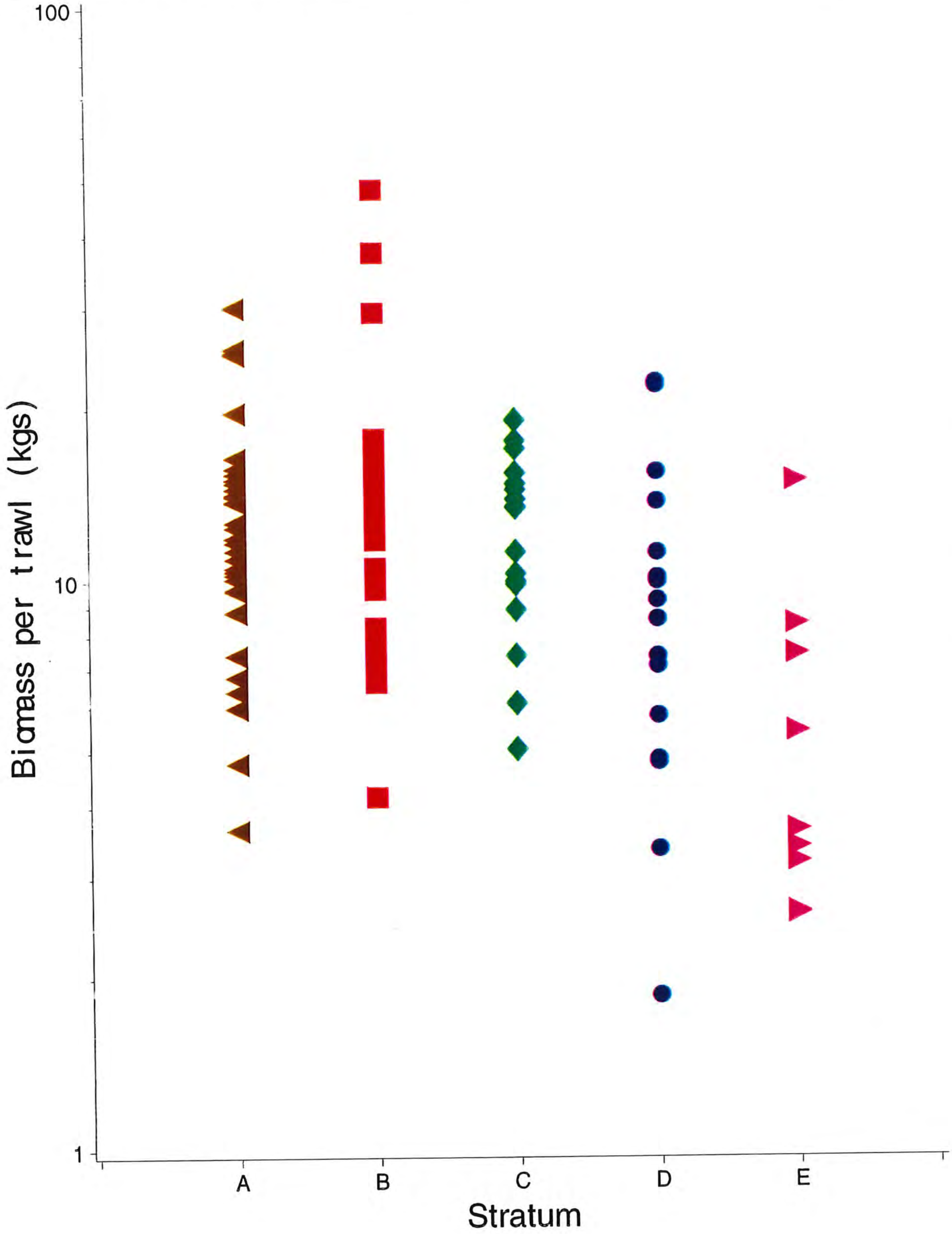


Figure 2.28 Total weight of species of crustaceans per prawn trawl tow for bycatch within each stratum in the study area of the Far Northern Section of the Great Barrier Reef (1992-1993).

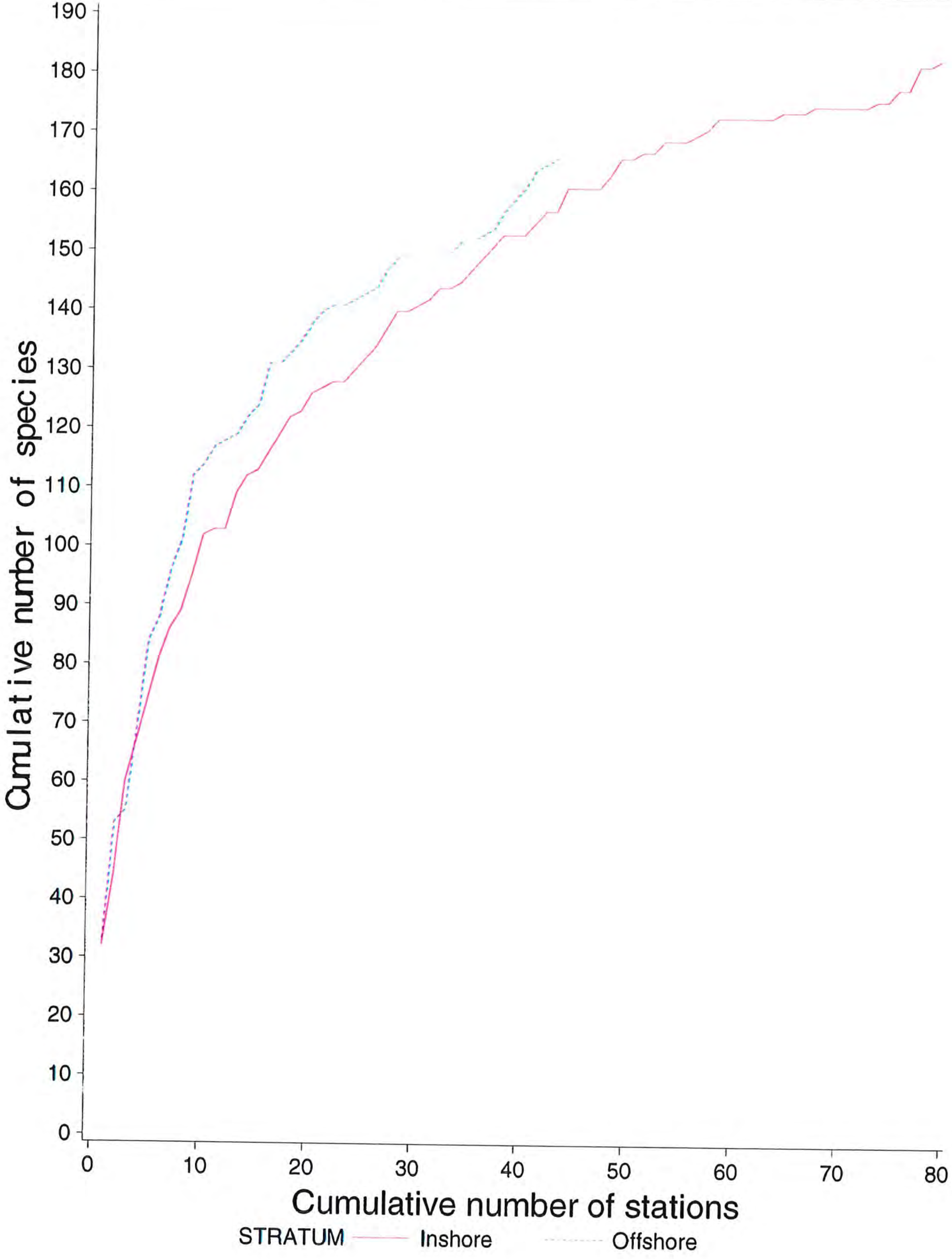


Figure 2.29 Species area curves for fish in the bycatch from prawn trawl tows made in inshore and offshore regions of the study area of the Far Northern Section of the Great Barrier Reef (1992-1993).

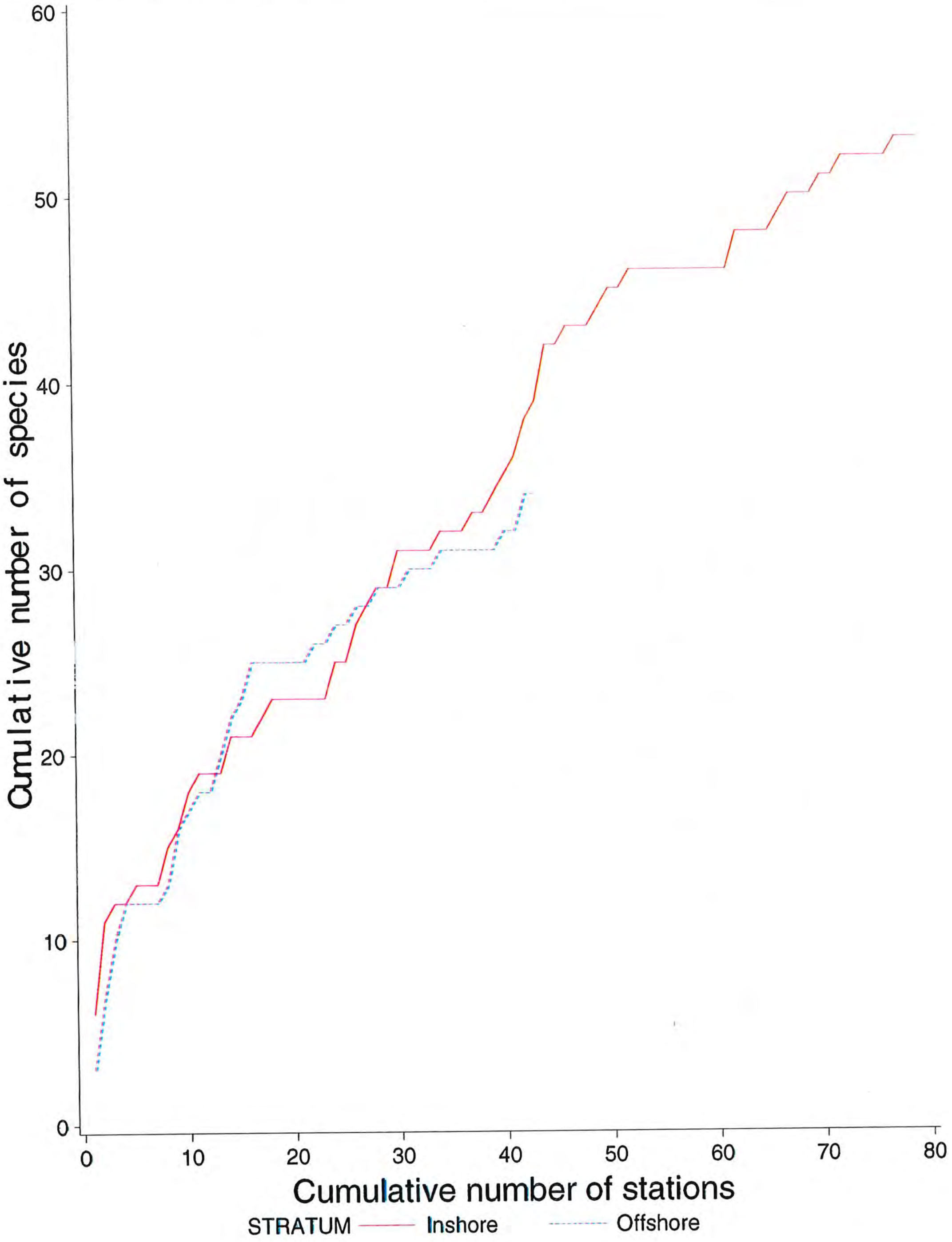


Figure 2.30 Species area curves for crustaceans in the bycatch from prawn trawl tows made in inshore and offshore regions of the study area of the Far Northern Section of the Great Barrier Reef (1992-1993).

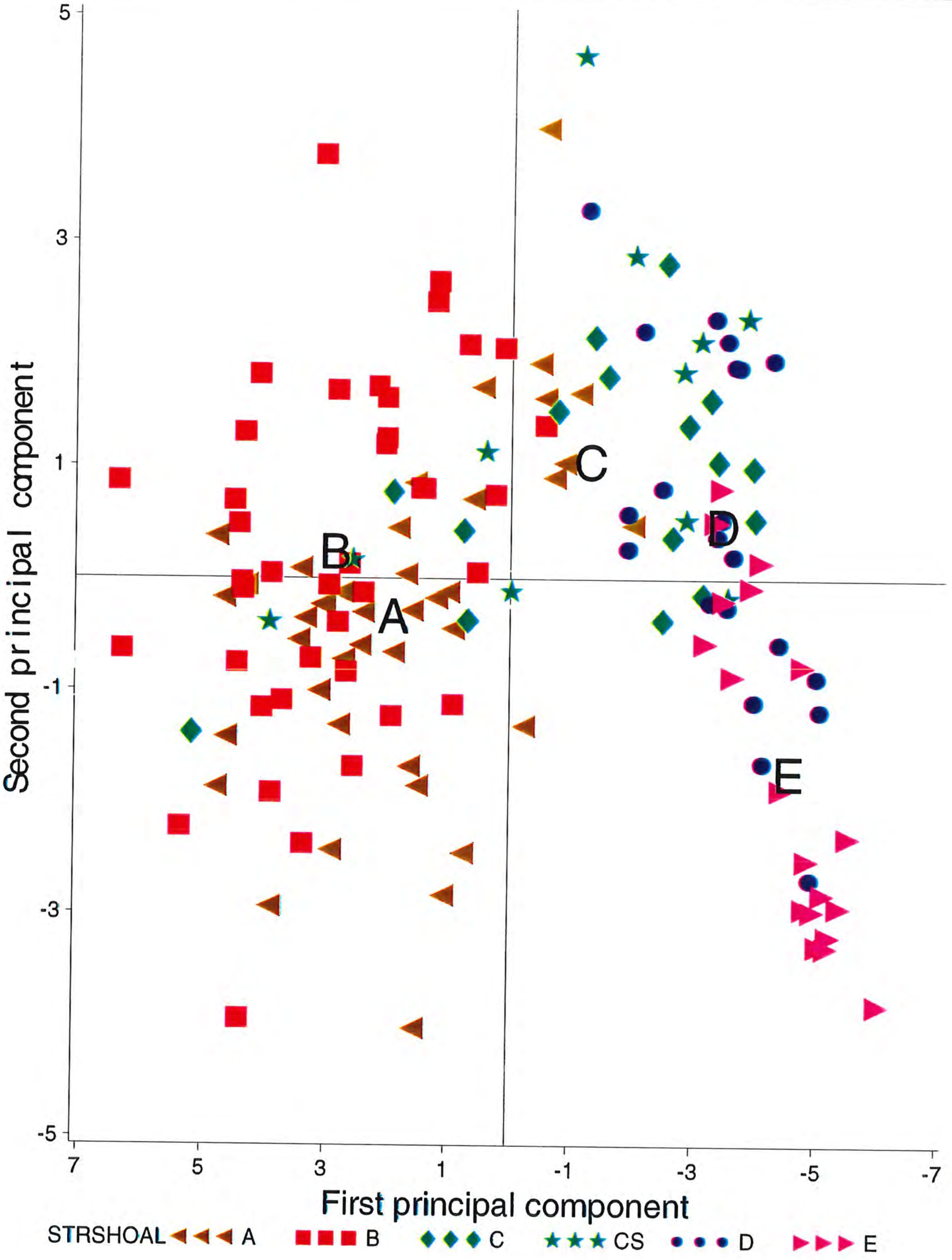


Figure 2.31 Plot of the principal component scores for stations of fish trawls within strata in the study area of the Far Northern Section of the Great Barrier Reef (1992-1993). The letters show the mean position for each stratum

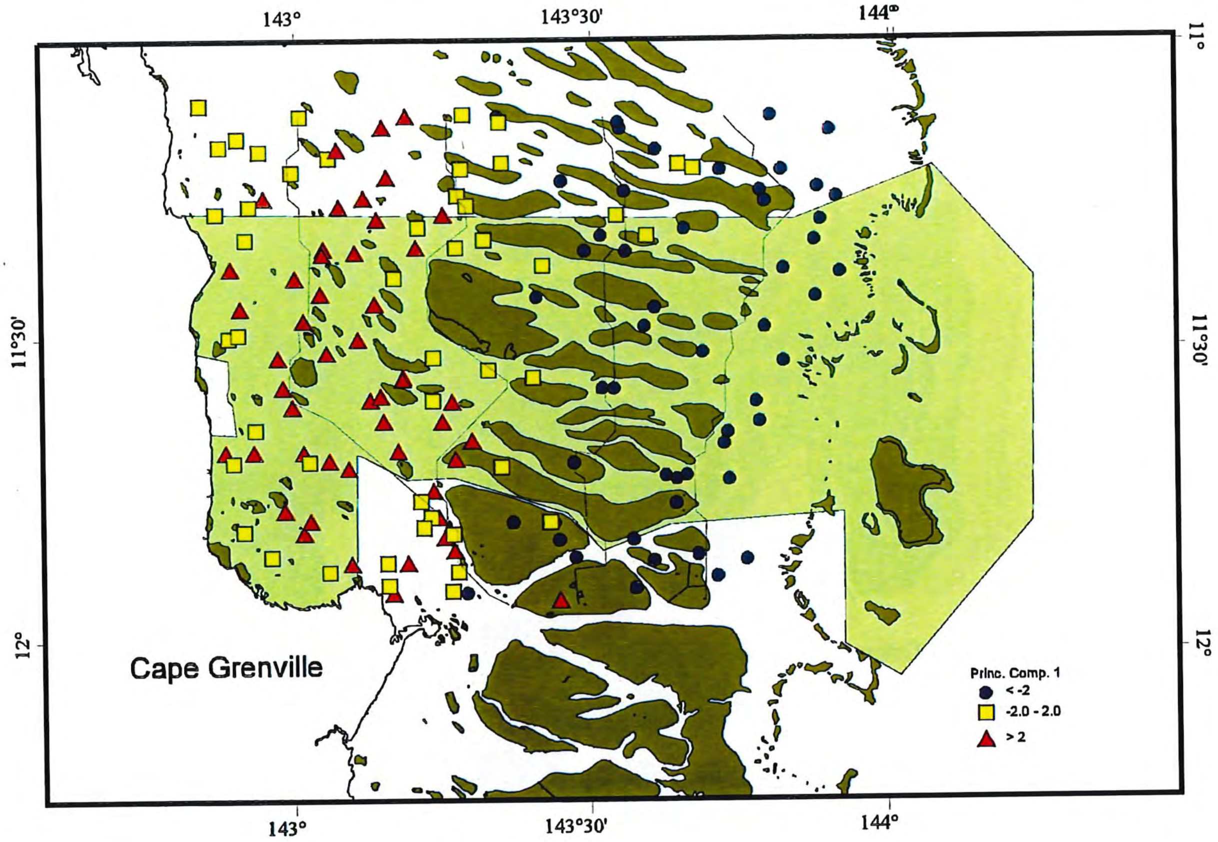


Figure 2.32 Species community profile according to the first principal component for fish from fish trawl tows overlaid on a map of the study area in the Far Northern Section of the Great Barrier Reef (1992-1993).

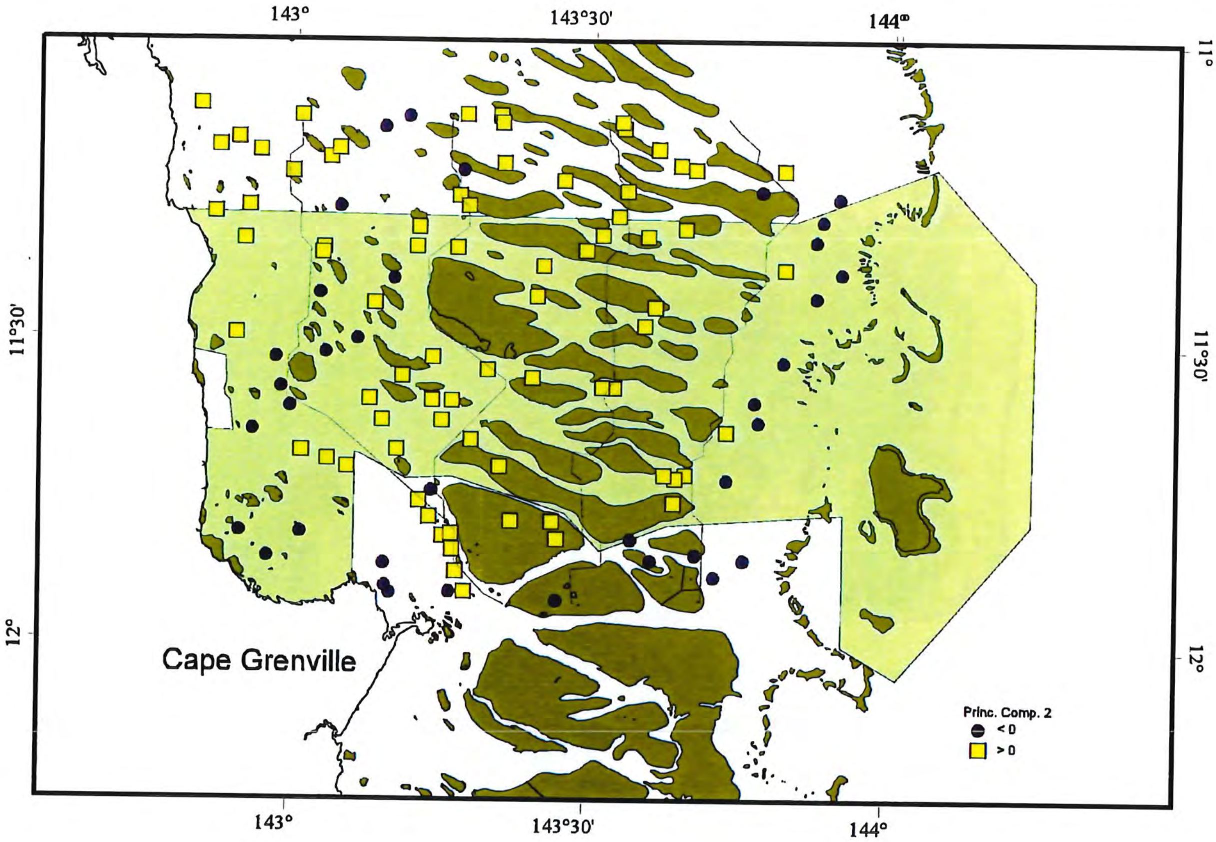


Figure 2.33 Species community profile according to the second principal component for fish from fish trawl tows overlaid on a map of the study area in the Far Northern Section of the Great Barrier Reef (1992-1993).

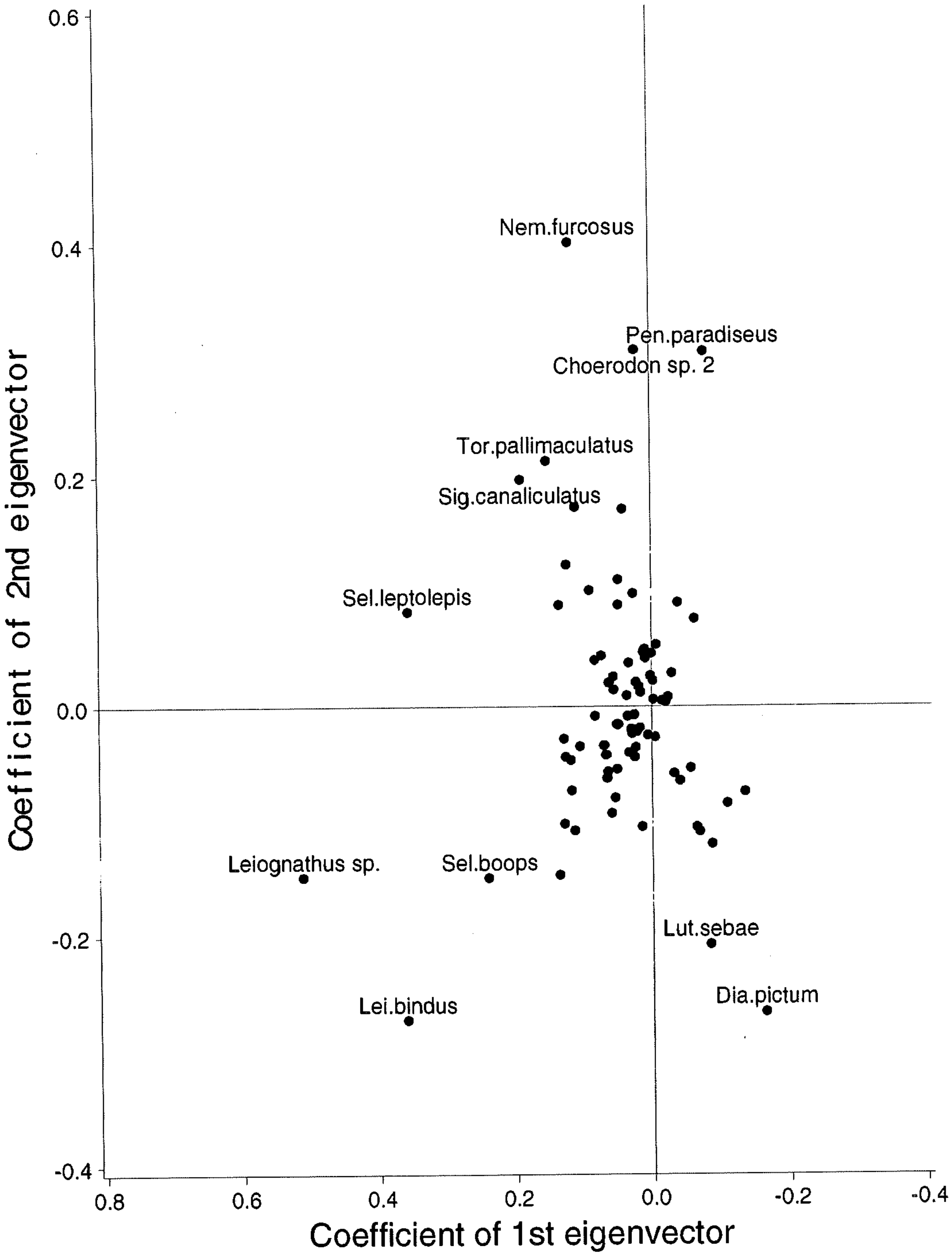


Figure 2.34 Eigenvector coefficients of fish species from the fish trawl in the study area of the Far Northern Section of the Great Barrier Reef, with outliers identified (1992-1993).

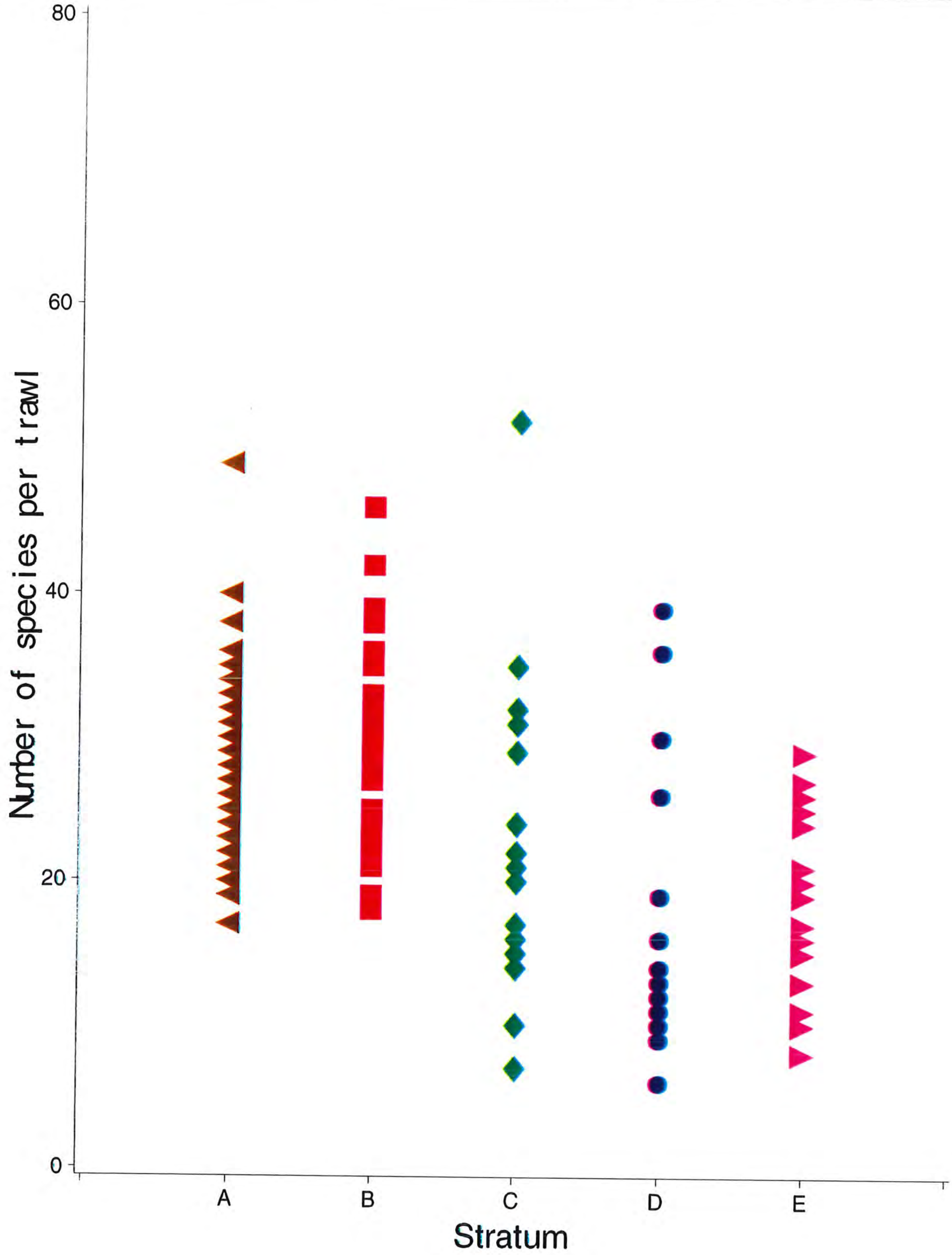


Figure 2.35 Number of species of fish per trawl tow for fish within each stratum in the study area of the Far Northern Section of the Great Barrier Reef (1992-1993).

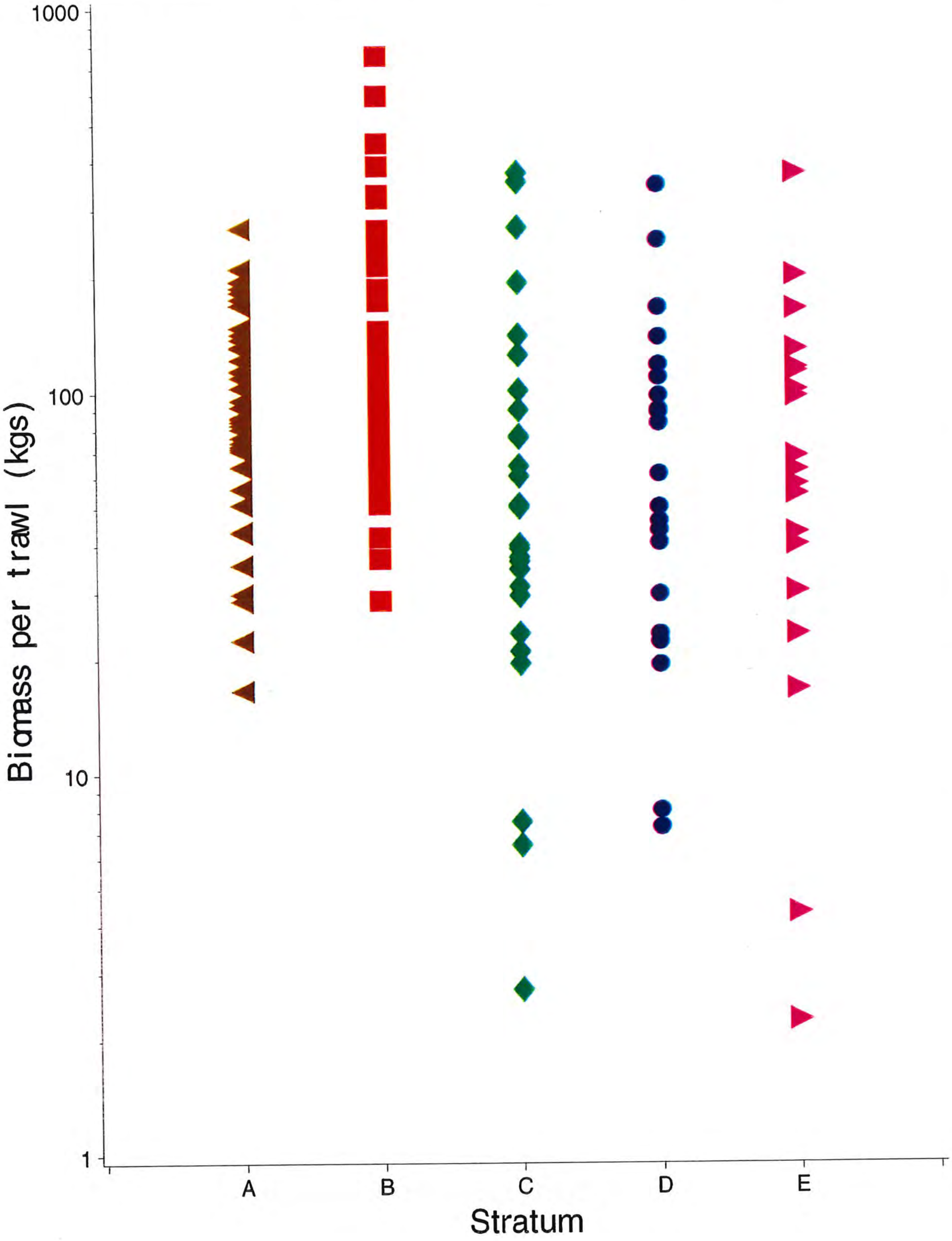


Figure 2.36 Total weight of species of fish per trawl tow for fish within each stratum in the study area of the Far Northern Section of the Great Barrier Reef (1992-1993).

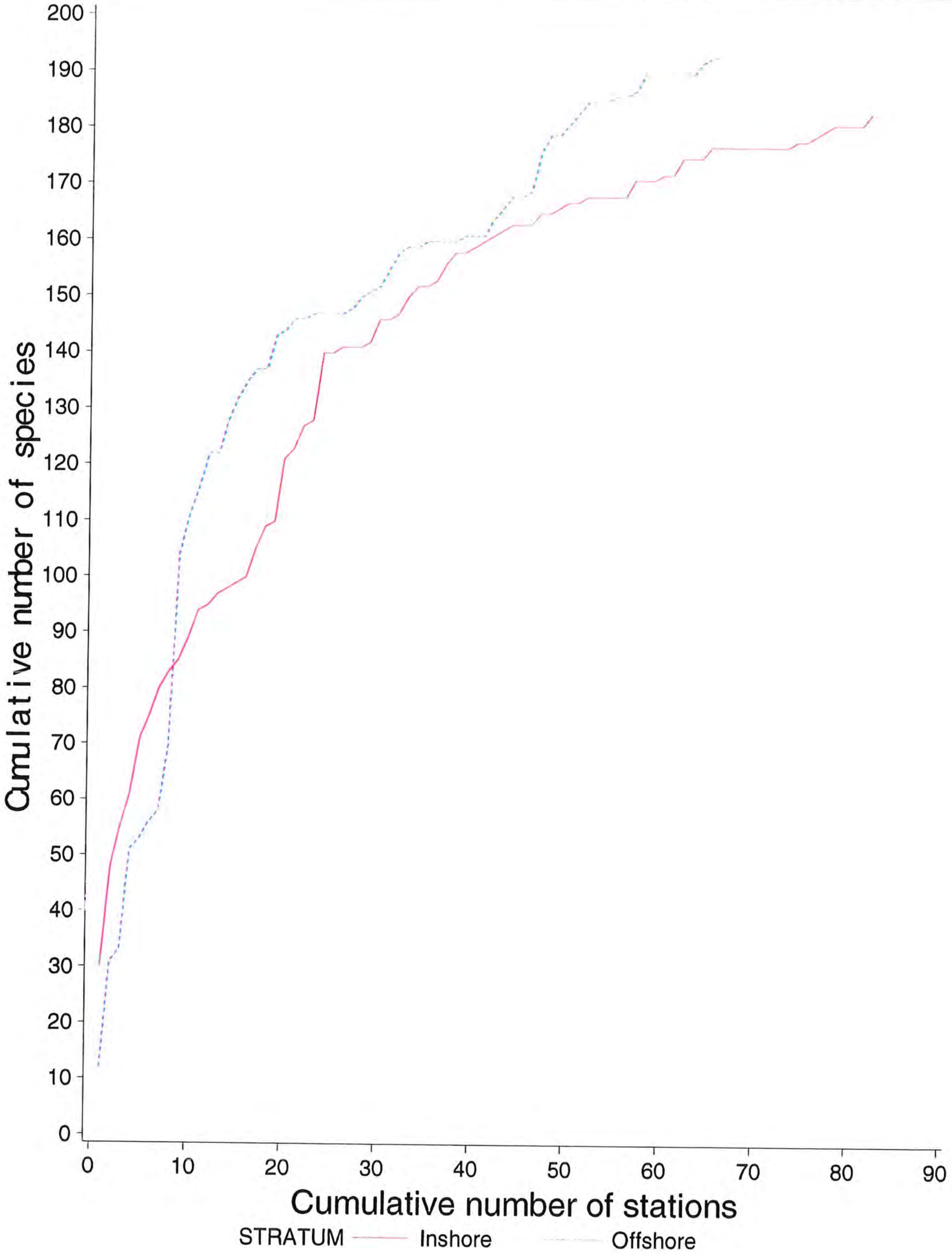


Figure 2.37 Species area curves for fish from fish trawl tows made in inshore and offshore regions of the study area of the Far Northern Section of the Great Barrier Reef (1992-1993).

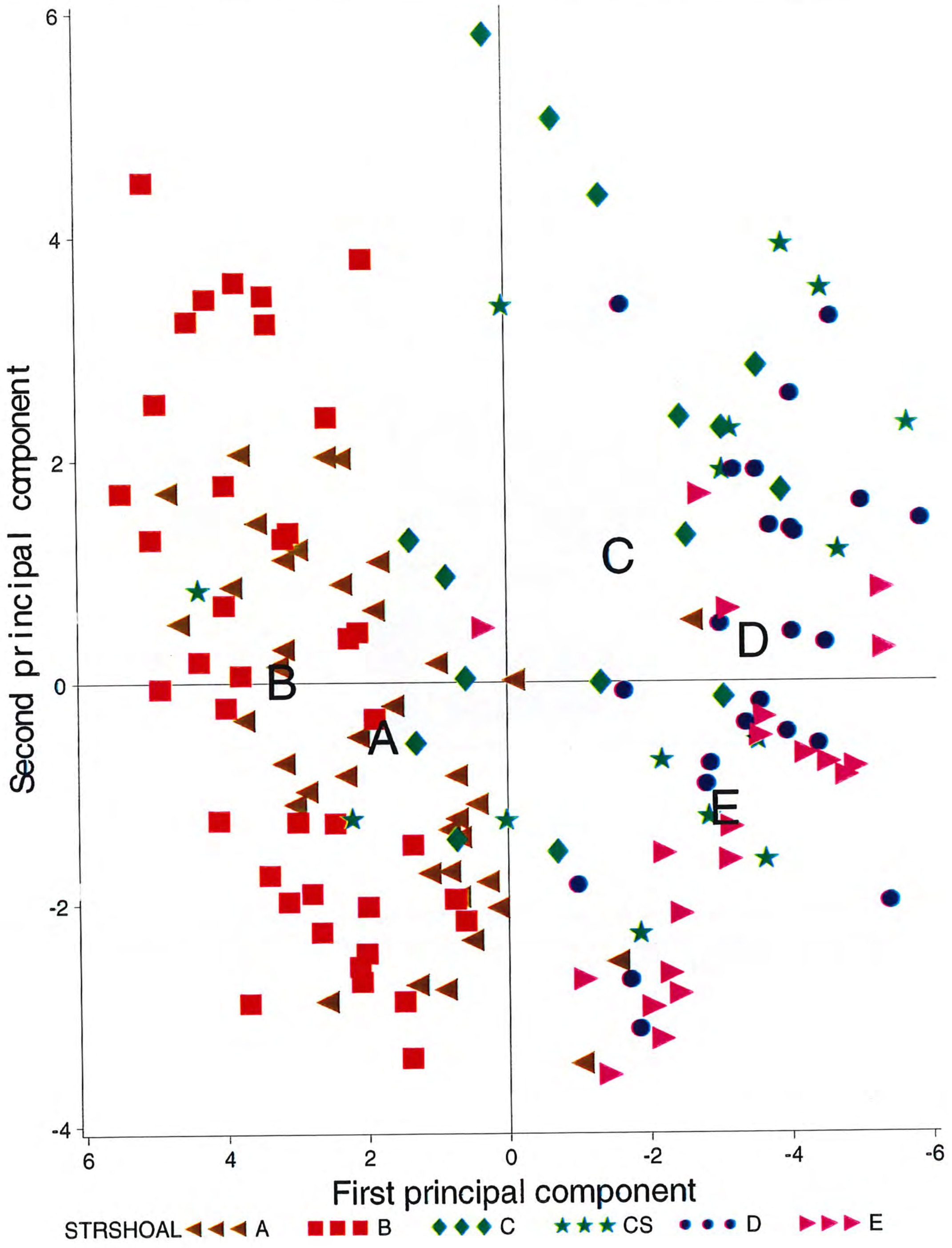


Figure 2.38 Plot of the principal component scores for benthic dredge stations within strata in the study area of the Far Northern Section of the Great Barrier Reef (1992-1993). The letters show the mean position for each stratum

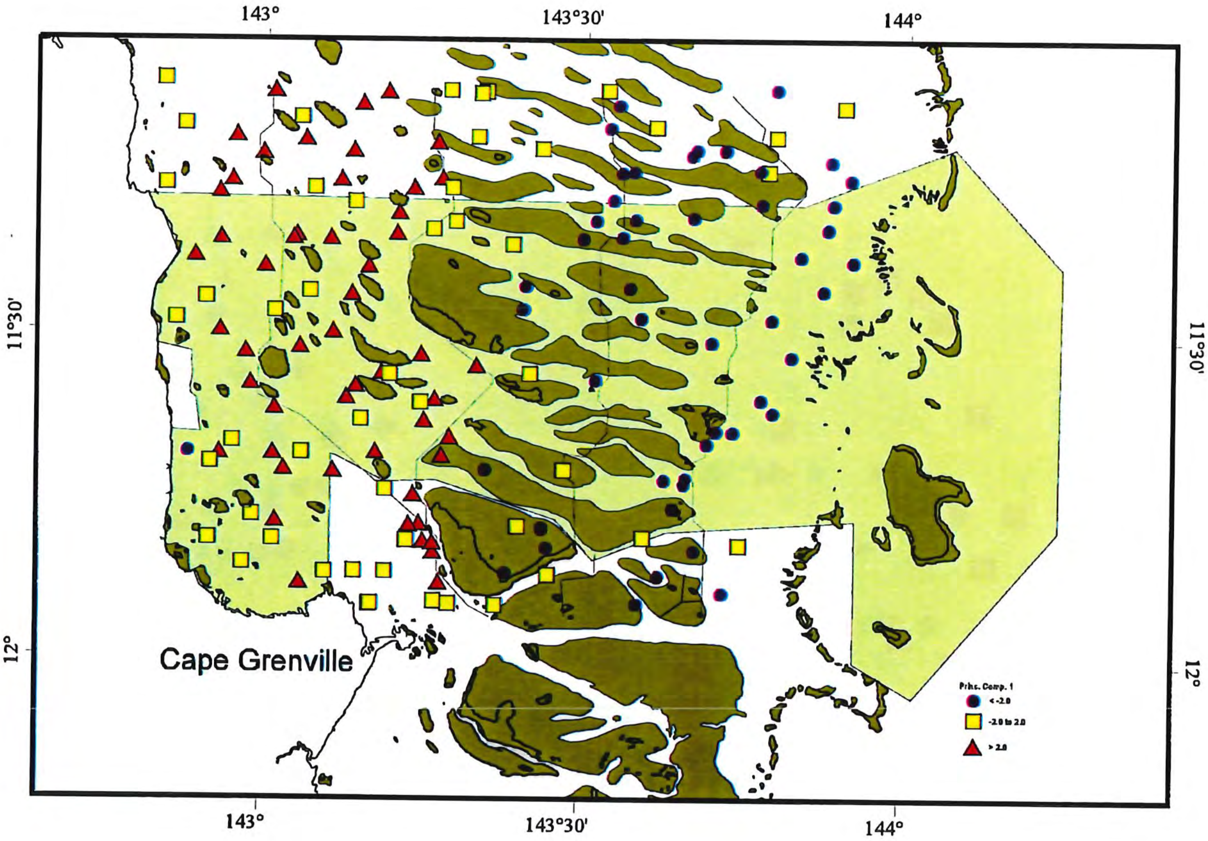


Figure 2.39 Species community profile according to first principal component for benthos collected from the dredge overlaid on a map of the study area in the Far Northern Section of the Great Barrier Reef (1992-1993).

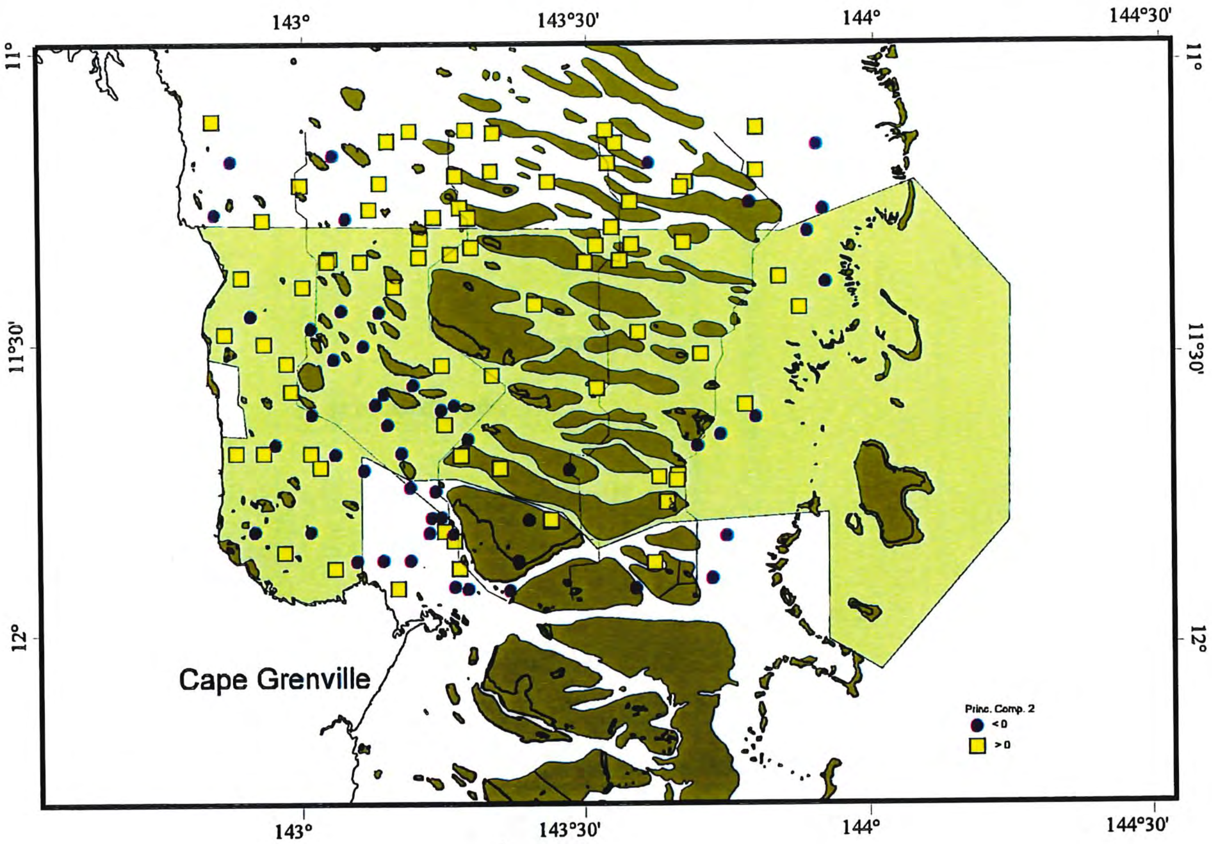


Figure 2.40 Species community profile according to second principal component for benthos collected from the dredge overlaid on a map of the study area in the Far Northern Section of the Great Barrier Reef (1992-1993).

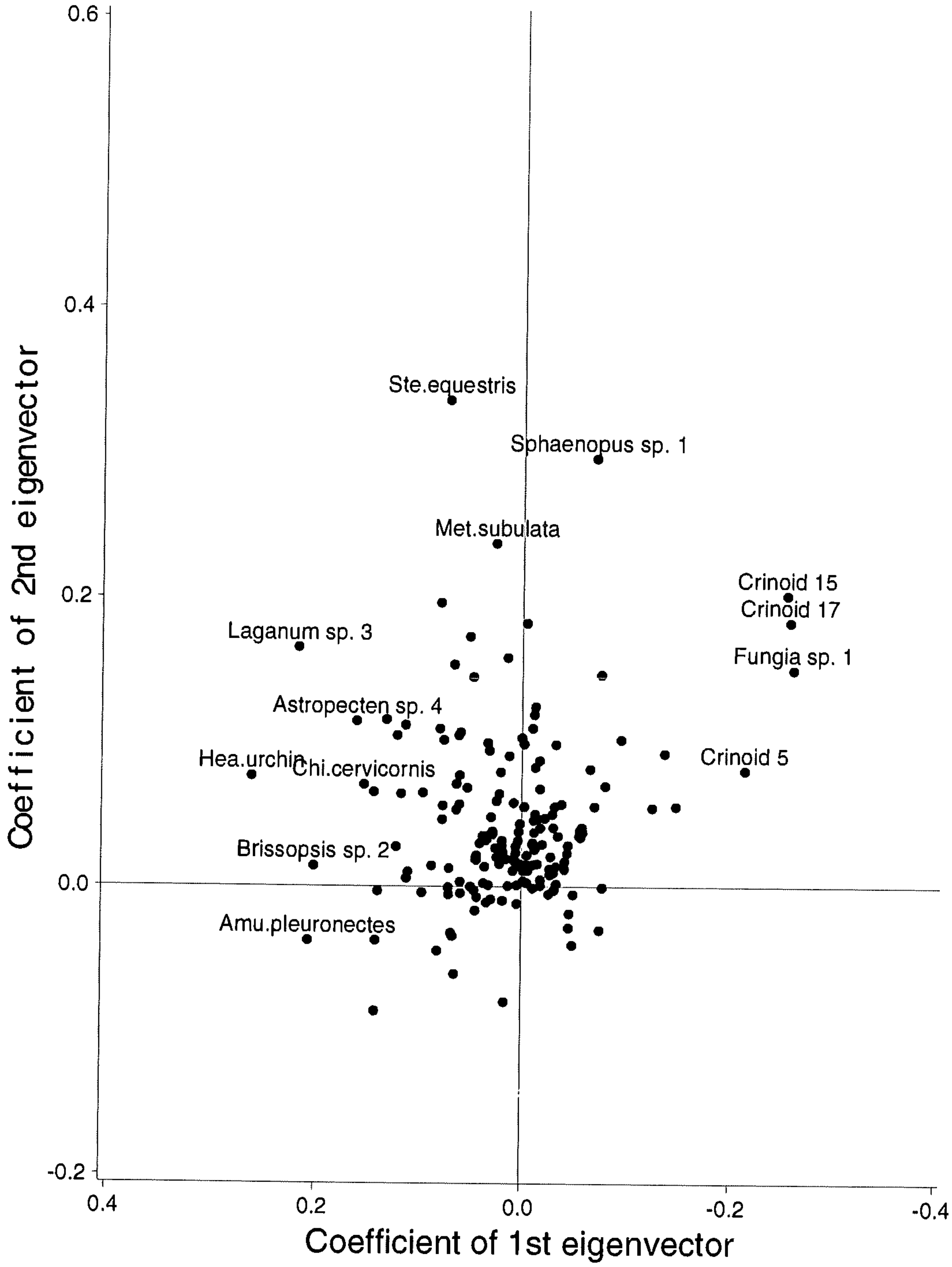


Figure 2.41 Eigenvector coefficients of species of benthos collected by the dredge in the study area of the Far Northern Section of the Great Barrier Reef (1992-1993) with outliers identified.

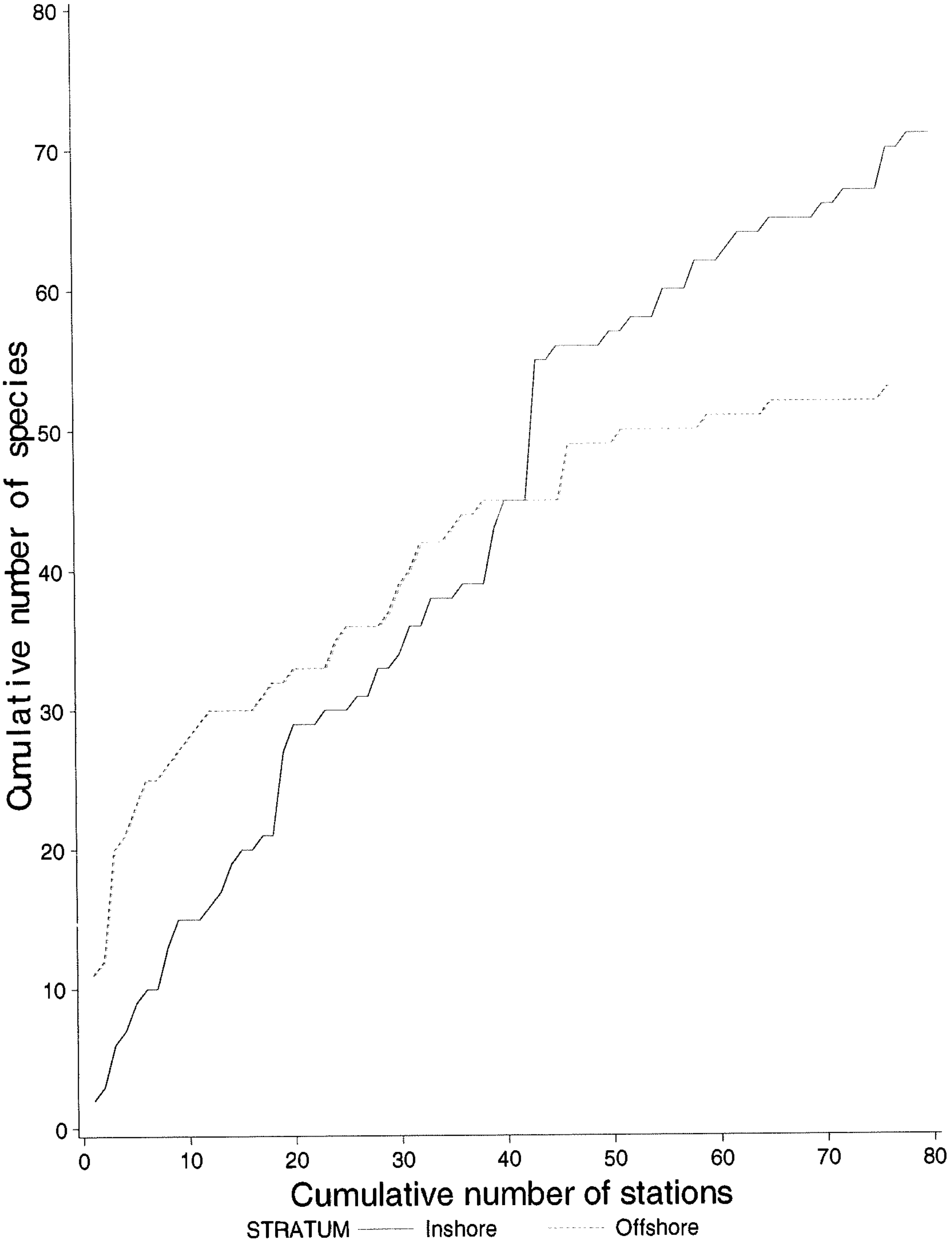


Figure 2.42 (a) Species area curves for Porifera species/taxa in the dredge for inshore and offshore areas in the study site of the Far Northern Section of the Great Barrier Reef (1992-1993).

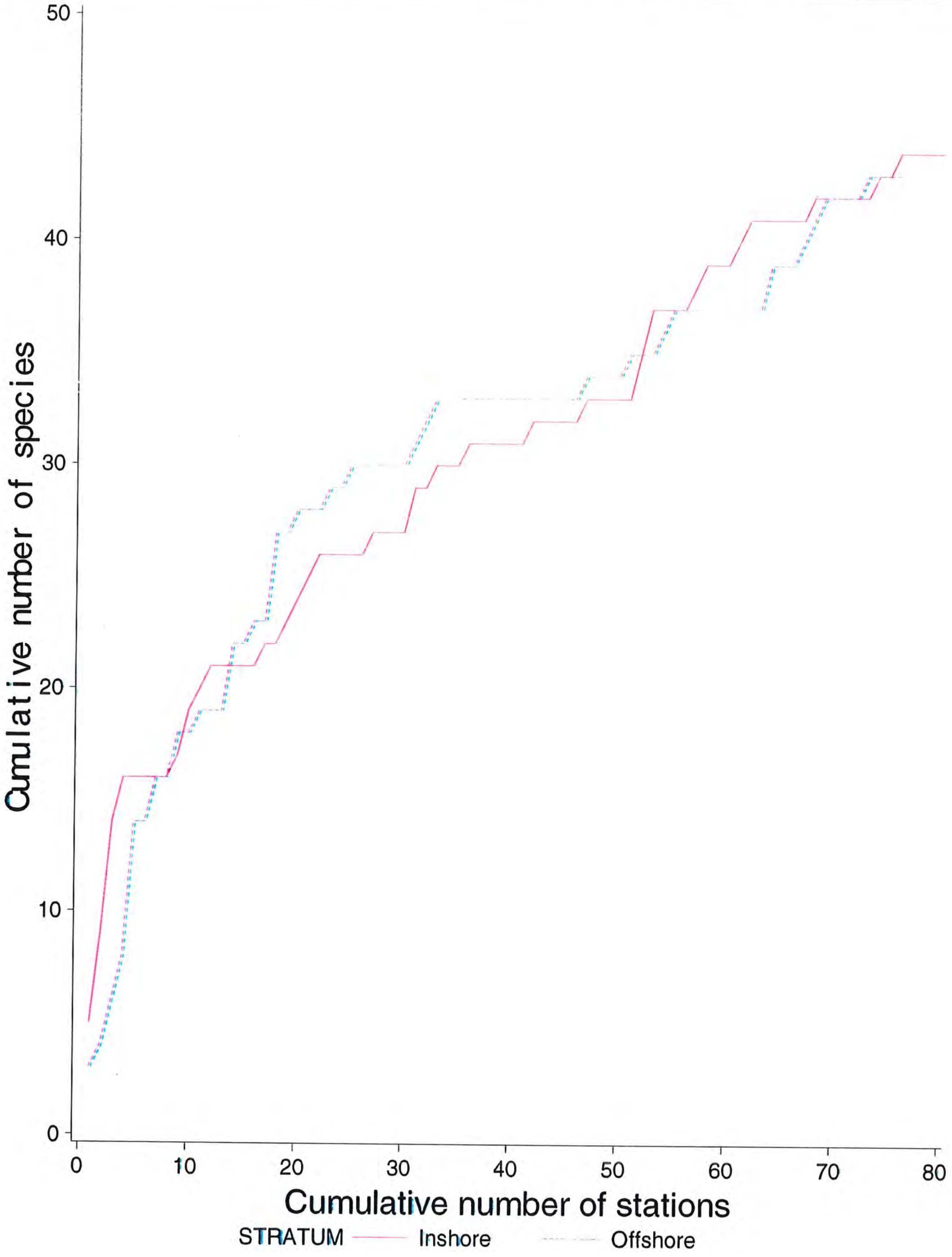


Figure 2.42 (b) Species area curves for Ascidian species/taxa in the dredge for inshore and offshore areas in the study site of the Far Northern Section of the Great Barrier Reef (1992-1993).

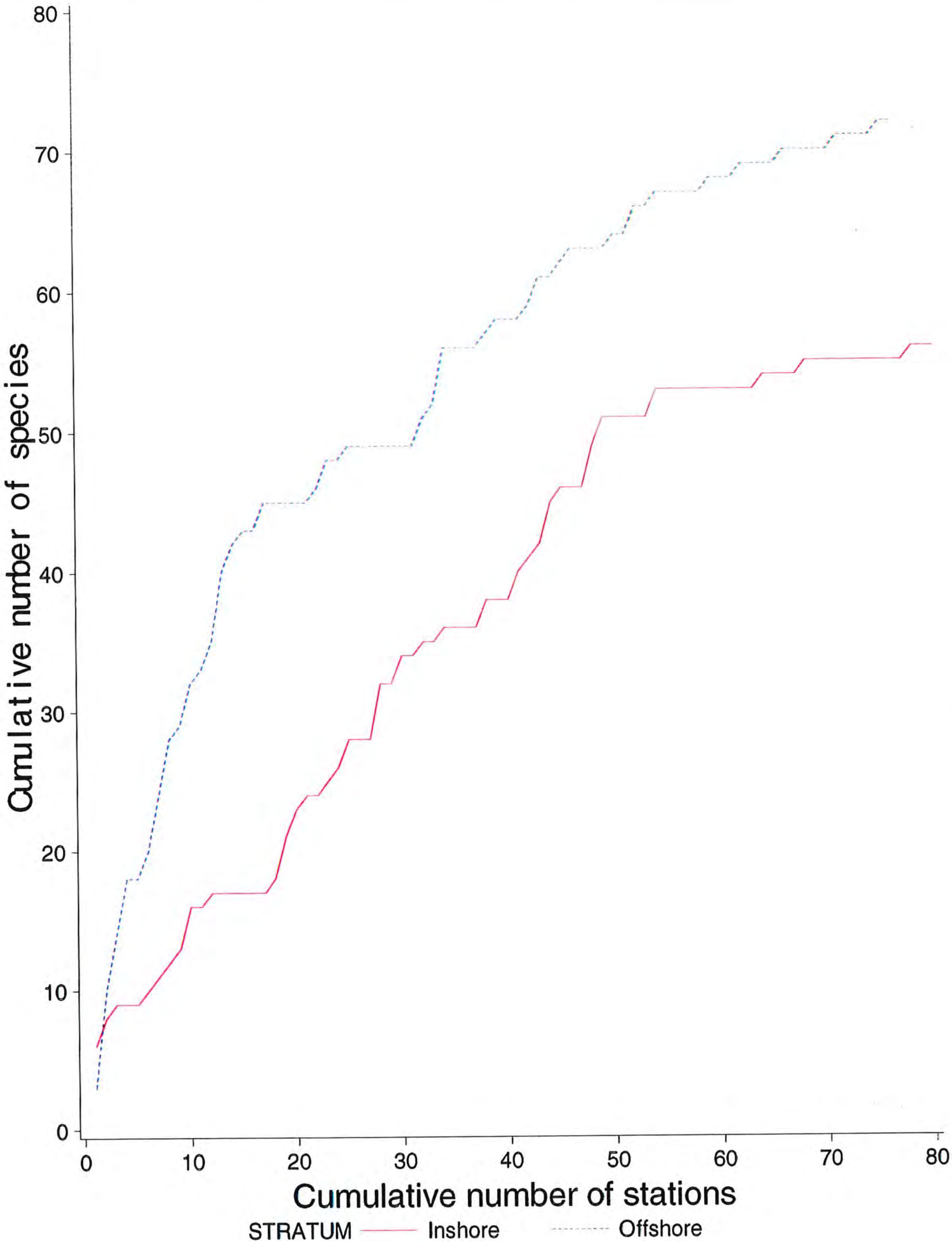


Figure 2.42 (c) Species area curves for Coral species/taxa in the dredge for inshore and offshore areas in the study site of the Far Northern Section of the Great Barrier Reef (1992-1993).

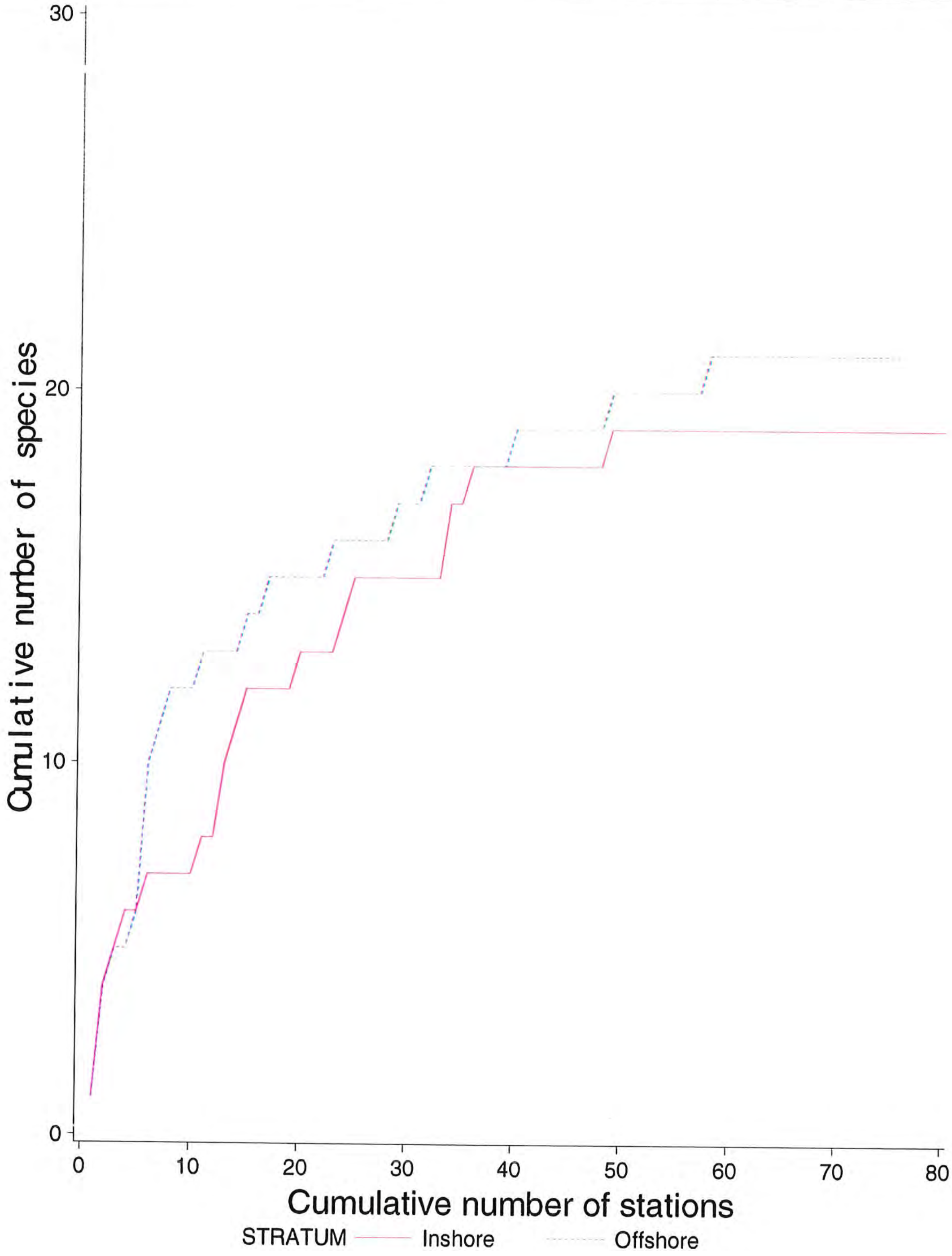


Figure 2.42 **(d)** Species area curves for Bryozoa species/taxa in the dredge for inshore and offshore areas in the study site of the Far Northern Section of the Great Barrier Reef (1992-1993).

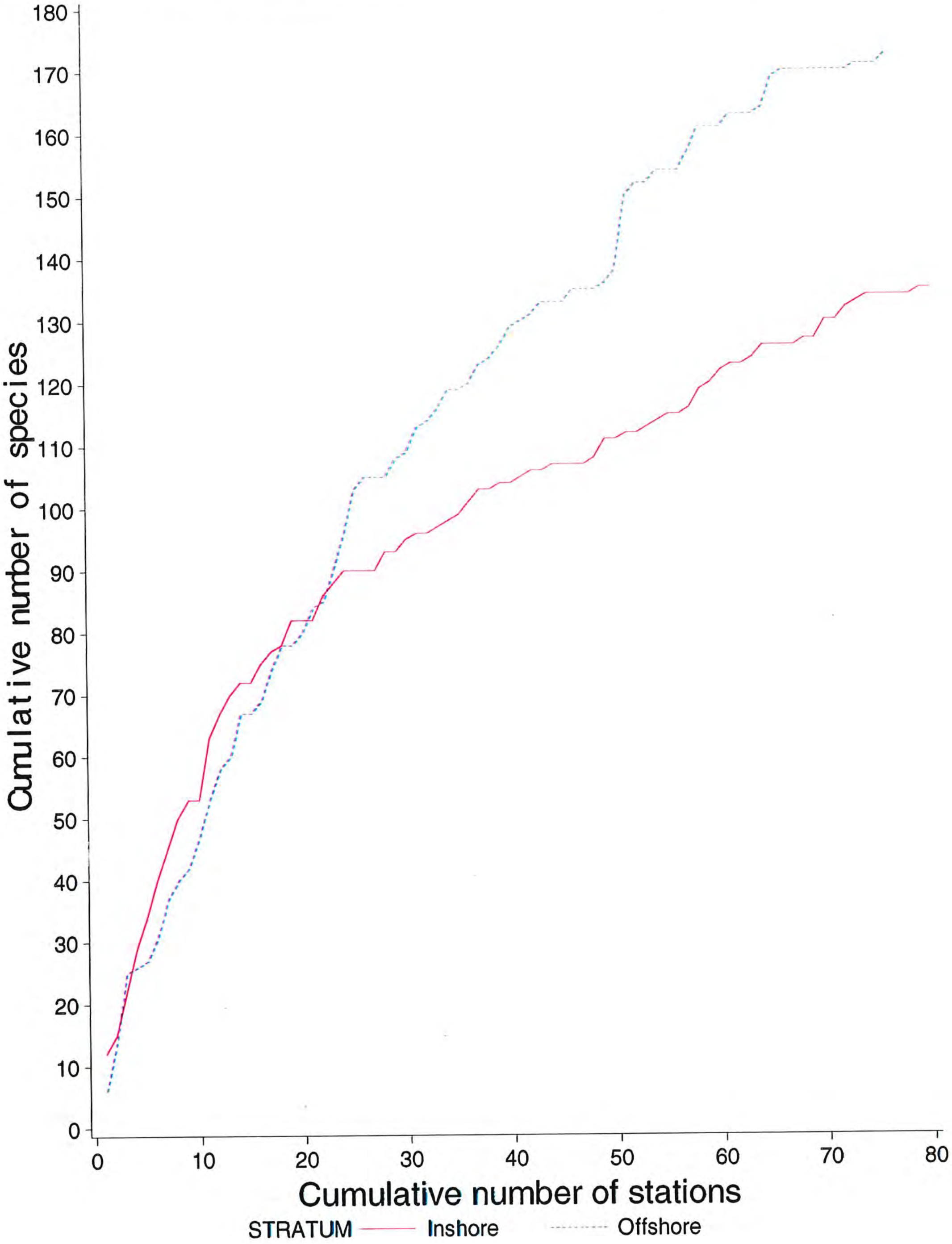


Figure 2.42 (e) Species area curves for Mollusca species/taxa in the dredge for inshore and offshore areas in the study site of the Far Northern Section of the Great Barrier Reef (1992-1993).

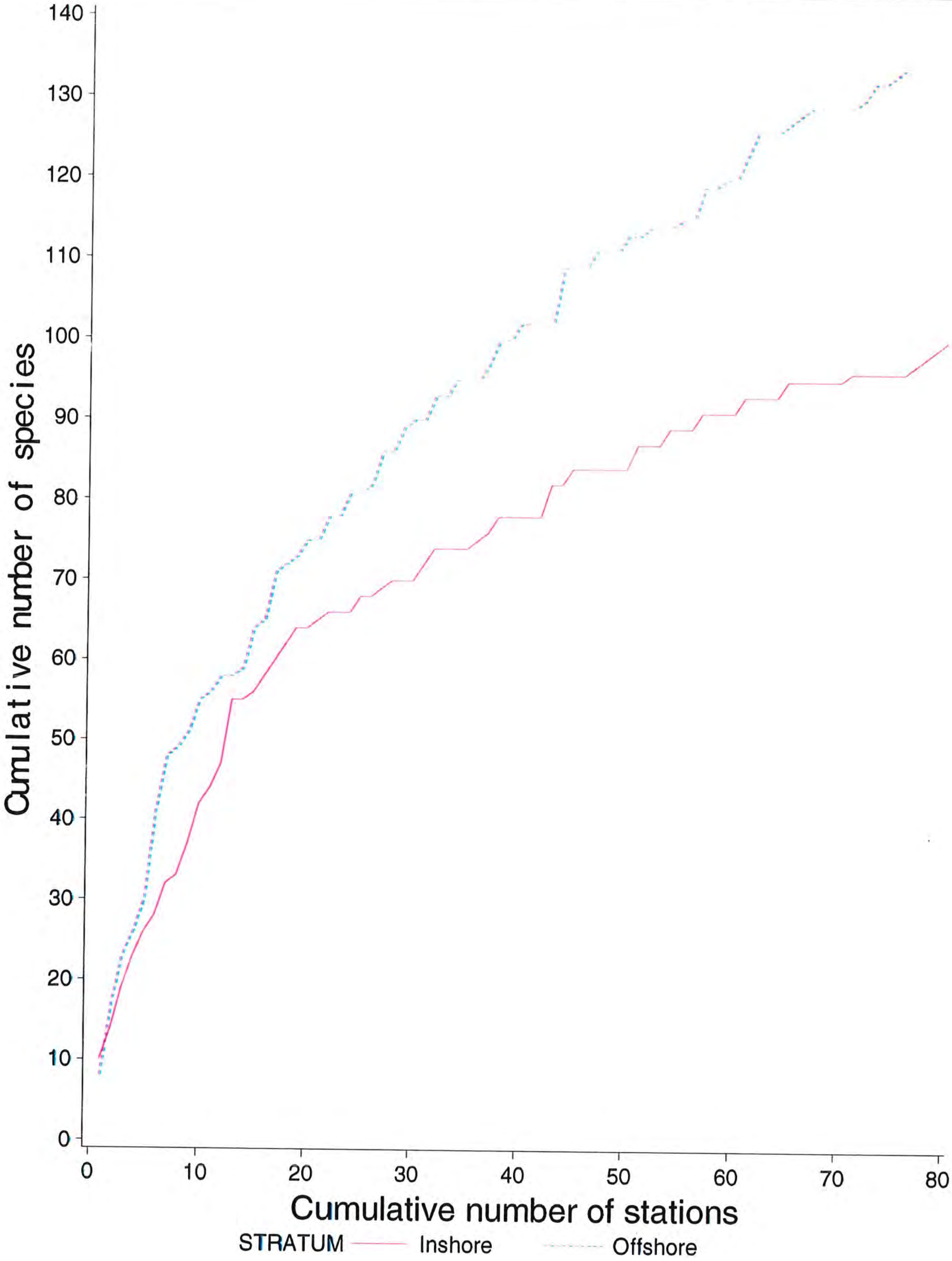


Figure 2.42 **(f)** Species area curves for Crustacean species/taxa in the dredge for inshore and offshore areas in the study site of the Far Northern Section of the Great Barrier Reef (1992-1993).

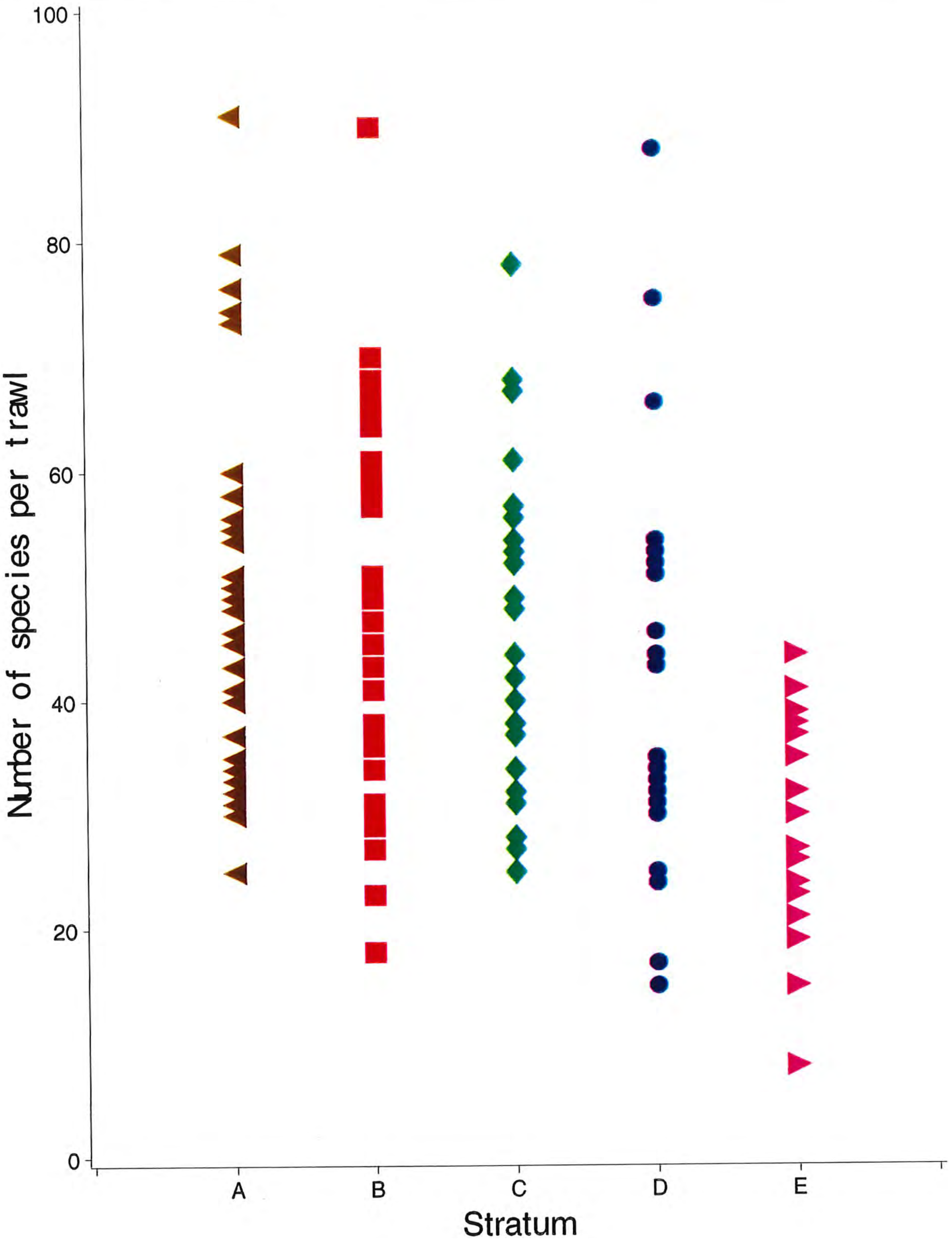


Figure 2.43 Number of species/taxa of benthos per dredge tow within each stratum in the study area of the Far Northern Section of the Great Barrier Reef (1992-1993).

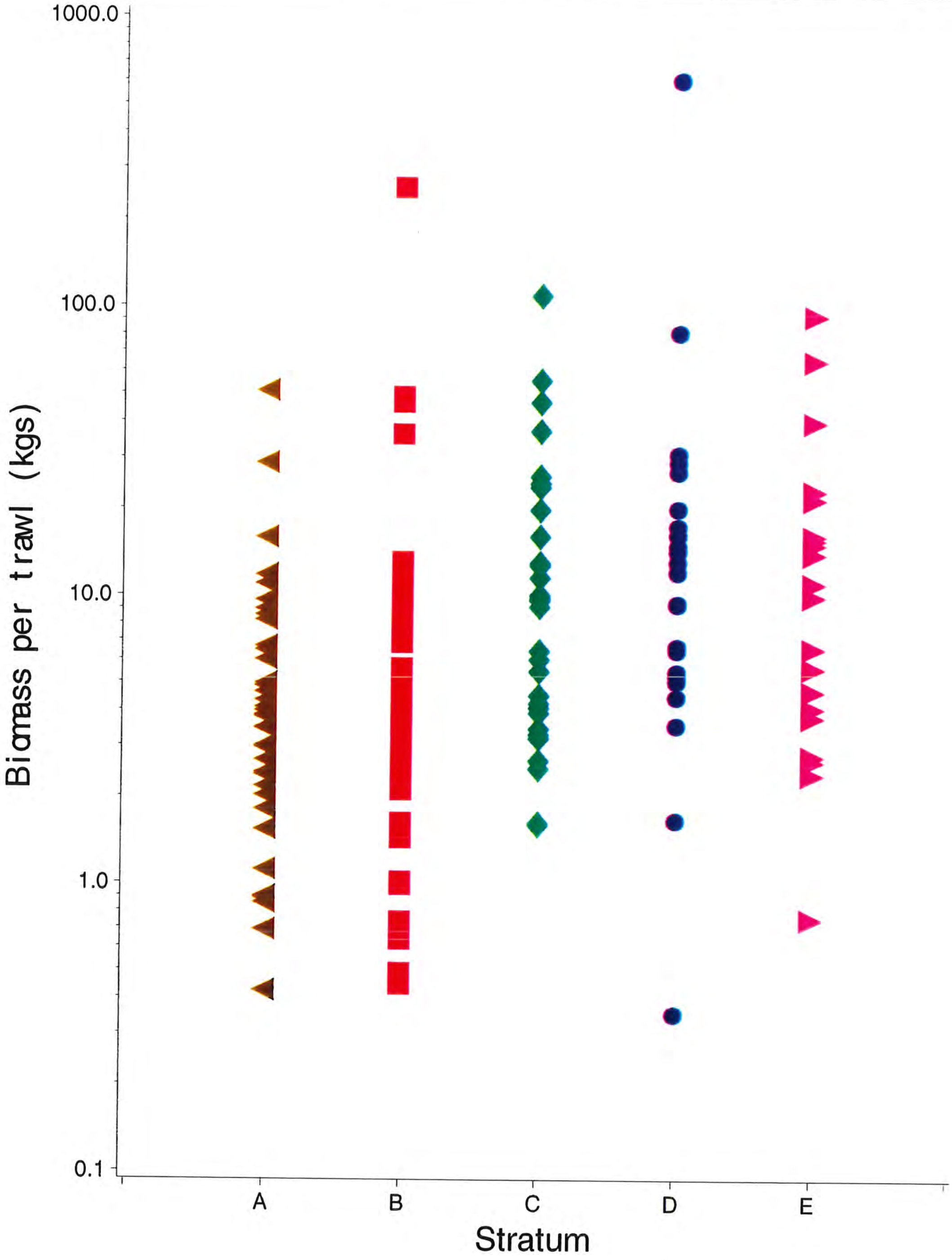


Figure 2.44 Total weight of species/taxa of benthos per dredge tow within each stratum in the study area of the Far Northern Section of the Great Barrier Reef (1992-1993).

APPENDIX.2.A

Table App.2.A.1 Differences between fish and prawn trawl catches (log-$_{10}$ transformed): fish species caught exclusively or in greater biomass by the fish trawl during the day in the Far Northern Section of the Great Barrier Reef. (l.C.L = lower confidence limit; u.C.L. = upper confidence limit; df = degrees of freedom; * indicates capture only by the fish trawl.)

Species	l.C.L	Mean	u.C.L.	df
Abalistes stellaris	0.19	1.34	2.49	8
Alepes sp	1.81	2.06	2.30	37
Atule mate *	1.14	1.66	2.18	10
Carangoides chrysophrys	0.96	1.51	2.06	15
Carangoides fulvoguttatus	1.39	1.57	1.75	18
Carangoides gymnostethus	1.28	1.48	1.67	34
Carangoides hedlandensis	1.77	1.96	2.16	45
Carangoides humerosus	1.39	1.64	1.90	41
Carangoides malabaricus	1.59	2.28	2.98	7
Carangoides talamparoides	1.32	1.68	2.04	18
Caranx bucculentus	0.89	1.44	1.99	34
Caranx caeruleopinnatus	1.83	1.99	2.15	33
Carcharhinus dussumieri *	2.35	2.52	2.69	7
Choerodon sp. 2	0.29	0.47	0.66	88
Decapterus russellii	0.78	1.18	1.57	31
Diagramma pictum	0.08	0.50	0.92	54
Dussumieria elopsoides *	1.69	1.91	2.14	26
Echeneis naucrates	1.82	2.05	2.28	24
Fistularia petimba	0.47	0.62	0.76	79
Gazza minuta	1.18	1.56	1.93	22
Gerres oyena	0.62	0.90	1.18	61
Glaucosoma magnificum	0.33	0.86	1.40	25
Gnathanodon speciosus	1.37	1.91	2.44	19
Gymnura australis	0.57	1.48	2.38	12
Herklotsichthys lippa	1.40	1.64	1.88	31
Himantura toshi	1.53	2.55	3.56	10
Leiognathus bindus	1.75	1.97	2.18	68
Leiognathus leuciscus	1.16	1.37	1.59	30
Leiognathus sp.	2.25	2.49	2.69	88
Lethrinus genivittatus	0.54	0.68	0.81	117
Lethrinus laticaudus	1.26	1.96	2.66	19
Lutjanus malabaricus	1.18	2.03	2.89	7
Lutjanus sebae	0.98	1.77	2.57	11
Lutjanus vittus	0.45	0.99	1.54	32
Mene maculata	1.63	2.11	2.60	15
Nemipterus furcosus	0.11	0.28	0.45	115
Nemipterus hexodon	0.15	0.46	0.77	44
Pentaprion longimanus	0.69	0.98	1.27	43
Platax batavianus	1.97	2.47	3.28	13
Pristotis jerdoni	0.03	0.34	0.65	40
Rachycentron canadum	1.06	2.46	3.86	6
Rastrelliger kanagurta	1.80	1.96	2.11	36

Species	l.C.L	Mean	u.C.L.	df
*Rhizoprionodon acutus**	1.97	2.43	2.90	17
Scomberomorus commerson	2.11	2.48	2.84	9
Scomberomorus munroi	2.04	2.36	2.67	11
Scomberomorus queenslandicus	2.46	2.57	2.68	66
Scomberomorus semifasciatus	2.46	2.82	3.17	9
Secutor insidiator *	0.63	1.11	1.58	9
Selar boops	1.77	2.07	2.37	57
Selar crumenophthalmus	1.56	1.92	2.28	7
Selaroides leptolepis	1.95	2.19	2.43	103
Seriolina nigrofasciata	1.41	1.89	2.36	23
Siganus canaliculatus	1.04	1.19	1.34	95
Sphyraena flavicauda	1.33	1.82	2.30	18
Sphyraena forsteri *	1.65	1.84	2.03	34
Upeneus moluccensis	0.02	0.48	0.94	13
Upeneus sulphureus	0.27	0.79	1.31	14
Uraspis uraspis *	1.34	1.65	1.96	9

Table App.2.A.2 Differences between fish and prawn trawl catches (log-$_{10}$ transformed): fish species caught exclusively or in greater biomass by the prawn trawl during the night in the Far Northern Section of the Great Barrier Reef. (l.C.L = lower confidence limit; u.C.L. = upper confidence limit; df = degrees of freedom; * indicates capture only by the prawn trawl.)

Species	l.C.L.	Mean	u.C.L.	df
Acentrogobius caninus	–1.01	–0.79	–0.58	15
Anacanthus barbatus	–0.52	–0.28	–0.04	11
Apistus carinatus	–1.10	–1.01	–0.91	78
Apogon brevicaudatus *	–0.64	–0.57	–0.49	38
Apogon ellioti	–1.08	–1.00	–0.92	90
Apogon fasciatus	–0.76	–0.64	–0.51	77
*Apogon melanopus**	–1.02	–0.72	–0.41	10
Apogon moluccensis *	–1.65	–1.04	–0.43	8
*Apogon nigripinnis**	–0.44	–0.31	–0.18	11
Apogon nigrocincta	–1.60	–0.88	–0.16	7
Apogon poecilopterus *	–0.87	–0.71	–0.56	22
Apogon septemstriatus	–0.22	–0.16	–0.11	34
Apogonidae	–1.53	–0.77	–0.01	7
Arothron manillensis	–1.57	–0.80	–0.02	6
*Callionymus belcheri**	–0.50	–0.38	–0.27	10
Callionymus grossi	–1.11	–1.03	–0.94	74
Callionymus japonicus *	–1.00	–0.84	–0.68	9
Canthigaster compressa	–0.64	–0.33	–0.02	20
Chaetoderma penicilligera *	–1.21	–0.95	–0.69	6
Cottapistus cottoides *	–0.67	–0.51	–0.36	6
Cyclichthys jaculiferus	–0.98	–0.56	–0.14	32
*Cymbacephalus nematophthalmus**	–1.34	–1.21	–1.07	11
Dactyloptena papilio	–0.85	–0.72	–0.59	37
Dactylopus dactylopus *	–0.77	–0.69	–0.62	47
Dasyatis leylandi	–1.15	–0.87	–0.59	36
*Engyprosopon grandisquama**	–0.91	–0.82	–0.73	85
Epinephelus sexfasciatus	–1.04	–0.94	–0.84	22
Euristhmus nudiceps *	–1.44	–1.35	–1.26	75
Grammatobothus polyophthalmus *	–0.89	–0.82	–0.74	40
Inimicus sinensis *	–0.90	–0.62	–0.34	7
Lepidotrigla argus	–1.15	–0.99	–0.83	22
*Minous versicolor**	–0.38	–0.29	–0.20	6
Monacanthus chinensis *	–0.61	–0.51	–0.41	11
Nemipterus peronii	–0.72	–0.49	–0.27	78
Paracentropogon longispinis	–0.65	–0.51	–0.36	31
Paramonacanthus choirocephalus	–1.13	–1.04	–0.94	111
Paramonacanthus japonicus	–0.65	–0.53	–0.41	104
Parapercis nebulosa	–1.14	–0.74	–0.34	14
Pegasus volitans *	–0.92	–0.64	–0.37	7
Pseudomonacanthus peroni	–0.98	–0.56	–0.14	28
Pseudorhombus argus	–1.15	–0.98	–0.82	45
Pseudorhombus arsius *	–1.46	–1.27	–1.07	7
Pseudorhombus diplospilus	–1.10	–0.92	–0.74	70
Pseudorhombus elevatus	–0.78	–0.61	–0.43	24
Pseudorhombus jenynsii	–1.27	–0.85	–0.43	13
Pseudorhombus spinosis	–1.25	–1.14	–1.03	84
Pseudorhorhombus dupliciocellatus	–1.34	–1.08	–0.83	26

Species	**l.C.L.**	**Mean**	**u.C.L.**	**df**
Rhynchostracion nasus	–0.98	–0.79	–0.59	75
Scolopsis taeniopterus	–1.16	–0.94	–0.72	89
Sillago ingennua	–1.13	–0.94	–0.75	36
Siphamia argyrogaster	–0.27	–0.21	–0.16	31
*Sorsogoma tuberculata**	–1.01	–0.93	–0.85	89
Suggrundus isacanthus	–1.24	–1.16	–1.08	84
Synchiropus rameus *	–1.01	–0.88	–0.75	35
Synodus hoshinonis	–0.79	–0.56	–0.32	23
Synodus sageneus	–0.85	–0.63	–0.41	55
Trachinocephalus myops	–0.85	–0.56	–0.27	28
Upeneus asymmetricus	–0.68	–0.39	–0.10	62
Upeneus tragula	–1.09	–0.94	–0.79	94
Youngeichthys nebulosus	–1.21	–0.99	–0.78	18

Table App.2.A.3 A comparison of mean size (cm) of fish caught by prawn trawl tows ($n = 122$) within each of the five strata in the Far Northern Section of the Great Barrier Reef. The number below n is the number of that species caught in each stratum. Species in bold indicate a significant linear or quadratic trend across the strata. (** = $P < 0.01$; *** = $P < 0.001$).

					Strata							
Species	**A** Size	*n*	**B** Size	*n*	**C** Size	*n*	**D** Size	*n*	**E** Size	*n*	**fit (P)**	**fit (P)**
Apogonidae					4.78	23	5.54	63	5.91	106		
Apistus carinatus	9.06	235	9.08	171	9.17	87	9.25	16				
Apogon ellioti	7.38	356	8.47	300	6.86	114						
Apogon fasciatus	6.68	308	6.92	304	5.83	12						
Callionymus grossi	13.01	275	15.25	71	15.05	41						
Canthigaster compressa					6.32	94	6.04	129	6.79	19		
Choerodon cephalotes	11.31	205	12.36	115	12.33	63	12.22	23	13.33	3	**	
Choerodon sp 2	10.28	47	10.98	64	10.08	49	9.94	32				
Cyclichthys jaculiferus	13.09	11	9.54	28	6.27	11						
Dactylopus dactylopus	9.38	58	10.19	21	10.09	11	10.8	5	9.3	3	*	*
Engyprosopon grandisquama	8.69	256	8.72	93	8.51	267	9.09	57	8.45	11		
Euristhmus nudiceps	25.99	181	26.05	396	26.73	11						
Fistularia petimba	31.31	67	31.38	102	32.42	33	36.5	2			**	
Lagocephalus sceleratus	12.26	82	12.59	80	13.07	15	11	17				
Lepidotrigla argus	10.44	45	11.39	18	10.54	35						
Lethrinus genivittatus	10.87	1504	11.67	1776	11.47	285	11.71	785	11.54	294	**	**
Nemipterus furcosus	13.35	1363	14.72	1354	14.96	463	15.04	134	14.87	38	***	***
Nemipterus peronii	10.61	263	11.88		13.14	28					***	
Paracentropogon longispinis	6.56	62	6.5	6	6.26	97	6.3	76	6	1	***	*
Paramonacanthus choirocephalus	6.56	1525	7.19	513	7.6	94	7.6	154	6.6	5	***	***
Paramonacanthus japonicus	7.74	365	8.5	210	8.91	64	9.25	111	7.6	3	***	*
Pentapodus paradiseus	11.78	284	12.58	375	13.47	339	13.38	164	12.38	29	***	**
Priacanthus tayenus	14.27	130	14.8	282	16.31	13						

Species					**Strata**							
	A		**B**		**C**		**D**		**E**		**fit (P)**	**fit (P)**
	Size	*n*	Size	*n*	Size	*n*	Size	*n*	Size	*n*		
Pristotis jerdoni	7.3	54	6.69	13	8.66	35	8.07	149	8.37	210		
Pseudorhombus argus	14.5	56			14.38	110	15.17	54				
Pseudorhombus diplospilus	15.28	89	14.37	79	16.13	15	19	1	21	1		***
Pseudorhombus spinosus	15.09	172	14.37	67	15.22	111	16.9	31	18	1	***	***
Rhynchostracion nasus	5.54	317	8.37	156	13.5	20	5.5	2			*	
Saurida undosquamis	17.9	409	18.94	335	19.75	177	24.15	131	24.26	39	***	
Scolopsis taeniopterus	9.41	1373	12.05	722	12.39	120						
Selaroides leptolepis	11.29	75	12.89	127	13.69	35	12.6	3			***	
Siganus canaliculatus	11.31	198	12.35	131	12.52	31	12.4	10			***	
Sillago ingennua	14.16	179	15	8	16.6	6	15.69	32	15.15	13	***	***
Sorsogona tuberculata	9.71	203	10.86	182	9.33	205	9.28	95	10	22		
Suggrundus isacanthus	14.85	190	15.94	132	16.71	41	18	2			***	
Synodus hoshinonis	12.29	14			14.49	35	12.28	43				
Synodus sageneus	15.65	63	15.32	31	14.04	23	14.9	10	14.1	8	*	
Torquigener pallimaculatus	8.69	233	9.93	198	10.53	102	10.44	52			***	
Trachinocephalus myops	13.17	18	13.25	4	15	8	15.38	40	12.84	19		***
Upeneus asymmetricus	11.24	364	12.27	291	12.57	35	11.97	72	11.53	19	***	***
Upeneus luzonius	11.81	127	12.7	23	12.68	19	13.47	49	12.54	39	***	*
Upeneus tragula	9.65	747	10.39	667	10.66	65	9.74	97	9.47	19	*	***
Yongeichthys nebulosus	11.05	21	11.76	25	12.18	28						
Number of prawn trawl tows	40		39		17		17		9			

APPENDIX.2.B

Table App.2.B.1 Listing of the percentage of occurrence, catch rate, standard deviation, mean size and standard deviation and the number of fish measured from prawn trawl catches in the Far Northern Section of the Great Barrier Reef (n = 122stations).

Species	**%**	**Catch rate ($g\ h^{-1}$)**	**s.d.**	**Mean size (cm)**	**s.d.**	***n***
Elasmobranchs						
Dasyatididae	1	2.2	24.3	17.0	–	1
Amphotistius kuhlii	2	6.1	51.3	25.8	7.2	36
Chiloscyllium punctatum	2	1.4	10.6	34.4	28.6	5
Dasyatis leylandi	27	97.6	228.8	18.0	4.6	283
Eucrossorhinus dasypogon	1	2.5	28.1	–	–	–
Gymnura australis	4	35.8	199.0	38.2	10.9	6
Himantura toshi	1	10.4	114.4	48.7	–	3
Rhizoprionodon acutus	1	2.2	24.7	31.0	–	1
Rhynchobatus djiddensis	1	8.5	93.8	119.0	–	3
Teleostii						
Antennariidae	1	0.2	2.0	5.7	–	3
Aploactinidae	5	1.4	8.1	6.5	2.3	13
Apogonidae	6	18.6	132.2	5.4	1.0	229
Balistidae	1	0.1	0.6	12.4	9.0	15
Cynoglossidae	1	0.5	5.8	12.0	–	2
Eleotridae	1	0.2	1.7	7.0	–	1
Labridae	1	0.3	3.8	8.0	–	2
Mullidae	2	4.8	42.1	–	–	–
Myliobatididae	1	1.0	10.9	27.0	–	1
Platycephalidae	1	0.1	1.1	14.5	6.6	10
Pomacentridae	1	0.4	3.9	6.0	–	2
Synodontidae	1	0.8	8.7	–	–	–
Abalistes stellaris	2	33.0	312.4	23.9	13.1	14
Acanthopegasus lancifer	1	0.4	4.7	10.8	1.0	6
Acentrogobius caninus	13	21.4	81.4	11.7	1.2	51
Adventor elongatus	3	1.6	9.2	7.7	1.8	13
Alectis indicu	1	1.0	11.3	–	–	–
Alepes sp.	2	9.4	61.5	20.0	1.7	6
Amblypomacentrus breviceps	2	0.6	4.5	3.9	0.8	194
Amblyrhynchotes spinosissimus	1	21.4	235.8	7.0	10.8	6
Anacanthus barbatus	8	3.7	14.2	20.3	4.8	42
Anchisomus multistriatus	4	49.7	422.6	8.2	5.5	120
Apistus carinatus	66	199.5	267.0	9.0	1.3	844
Apogon albimaculosus	2	0.5	3.5	6.2	0.8	5
Apogon aureus	2	14.9	163.4	7.1	1.7	291
Apogon brevicaudatus	32	21.7	41.5	7.4	1.6	784
Apogon ellioti	74	220.1	285.0	7.2	2.2	1630
Apogon exostigma	1	0.1	1.3	6.0	–	1
Apogon fasciatus	62	100.9	139.3	6.8	1.6	928
Apogon fraenatus	3	4.5	33.8	7.0	1.3	24
Apogon hartzfeldii	2	0.2	1.2	4.5	0.9	380
Apogon melanopus	9	11.6	53.3	8.1	1.2	37
Apogon moluccensis	8	24.7	123.9	5.8	0.8	235
Apogon nigripinnis	8	1.9	7.4	5.9	1.1	70
Apogon nigrocincta	7	26.8	181.6	5.3	0.8	1678
Apogon poecilopterus	19	27.6	82.8	7.5	1.9	139
Apogon semilineatus	5	2.9	17.7	6.8	1.4	153

Species	*%*	**Catch rate (g h^{-1})**	**s.d.**	**Mean size (cm)**	**s.d.**	*n*
Apogon septemstriatus	29	3.7	9.9	4.5	0.9	230
Archamia fucata	3	14.4	145.3	6.1	0.7	141
Arothron aerostaticus	7	8.8	35.7	8.1	2.2	17
Arothron hispidus	1	1.3	14.7	9.2	7.0	59
Arothron manillensis	5	14.3	77.9	10.1	5.0	34
Arothron stellatus	2	14.7	128.0	17.2	7.0	42
Aseraggodes melanostictus	2	0.9	5.9	9.7	–	3
Asterhombus intermedius	2	1.0	7.5	9.6	0.8	10
Brachaluteres jacksoniensis	1	1.0	11.2	4.5	–	2
Callionymus belcheri	9	3.1	12.1	8.4	1.5	32
Callionymus grossi	61	175.8	226.8	13.7	2.0	511
Callionymus japonicus	8	12.1	48.3	13.8	2.8	58
Callionymus moretonensis	5	8.8	56.6	10.9	1.4	40
Callionymus sublaevis	1	0.3	3.3	12.0	–	1
Canthigaster compressa	13	104.9	845.1	5.0	1.0	4812
Canthigaster rivulata	3	1.7	11.6	5.1	1.2	78
Carangoides chrysophrys	2	3.0	23.1	16.1	8.7	16
Carangoides gymnostethus	1	1.2	13.6	14.0	–	1
Carangoides hedlandensis	2	1.6	12.8	11.3	–	3
Carangoides humerosus	5	11.1	53.2	14.9	4.5	16
Carangoides talamparoides	1	1.4	15.0	8.0	–	3
Caranx bucculentus	11	29.0	119.8	12.8	2.5	47
Centriscus scutatus	18	3.9	11.5	14.3	3.7	239
Chaetoderma penicilligera	6	11.9	58.6	7.8	3.3	170
Chaetodon kleinii	1	0.5	5.0	8.0	–	1
Chaetodontoplus duboulayi	3	9.5	65.8	11.8	3.1	321
Chelmon marginalis	1	0.6	6.5	11.9	1.7	42
Choerodon cephalotes	65	444.4	554.5	11.7	3.0	2093
Choerodon monostigma	12	14.0	46.2	10.0	1.7	67
Choerodon sp.2	54	109.8	165.7	8.6	2.0	1562
Cookeolus boops	2	0.5	4.2	9.3	–	3
Coradion chrysozonus	7	6.7	35.0	7.0	2.0	199
Cottapistus cottoides	6	3.5	16.1	6.7	1.3	124
Crossorhombus azureus	2	1.7	13.9	8.2	1.5	104
Cymbacephalus nematophthalmus	10	32.5	106.4	22.3	4.9	58
Cynoglossus macrophthalmus	2	1.8	11.2	14.4	1.5	5
Cynoglossus maculipinnis	1	0.4	4.0	13.7	–	3
Cynoglossus sp.	2	1.8	14.3	12.8	–	4
Dactyloptena papilio	31	37.5	84.2	8.7	2.2	185
Dactylopus dactylopus	40	41.2	70.9	9.5	1.9	203
Dascyllus trimaculatus	2	4.0	32.2	7.5	1.2	8
Decapterus macrosoma	1	1.5	16.5	17.0	–	1
Decapterus russellii	7	49.8	311.5	16.4	2.5	59
Dendrochirus brachypterus	3	1.1	7.1	5.4	2.3	39
Dendrochirus zebra	1	2.0	22.0	14.8	1.9	6
Diagramma pictum	29	80.9	204.1	16.0	10.7	371
Echeneis naucrates	2	3.8	29.5	41.6	13.5	15
Encrasicholina heterolobus	1	0.1	0.7	4.9	0.6	9
Engyprosopon grandisquama	71	163.8	311.6	8.6	1.1	1069
Engyprosopon macroptera	1	2.4	26.7	10.0	1.7	53
Epinephelus sexfasciatus	19	37.5	93.3	12.9	2.8	50
Escualosa thoracata	1	0.1	1.1	6.0	–	4
Euristhmus nudiceps	61	429.3	602.5	25.7	4.5	946
Fistularia commersonii	1	0.3	2.8	31.9	14.0	56
Fistularia petimba	49	73.7	99.5	31.7	4.2	338
Fowleria abocellata	1	0.0	0.2	3.3	0.6	572
Gazza minuta	2	3.1	23.9	9.8	1.0	8
Gerres filamentosus	2	1.1	9.0	11.8	1.1	22
Gerres oyena	26	94.6	287.8	11.7	1.6	209
Gerres subfasciatus	1	6.5	72.1	10.5	1.0	13
Glaucosoma magnificum	7	15.3	73.3	10.4	1.8	488

Species	*%*	**Catch rate ($g\ h^{-1}$)**	**s.d.**	**Mean size (cm)**	**s.d.**	*n*
Gnathanodon speciosus	1	0.5	5.3	7.6	3.5	25
Grammatobothus polyophthalmus	34	49.2	89.1	11.5	2.6	151
Haliichthys taeniophorus	1	0.2	2.2	21.0	6.0	24
Herklotsichthys lippa	1	0.1	1.6	10.1	1.3	7
Inimicus caledonicus	1	0.1	1.4	8.6	2.2	111
Inimicus sinensis	7	6.7	46.6	8.2	1.1	33
Lactoria cornuta	2	4.4	37.1	11.9	7.0	103
Lagocephalus lunaris	2	89.7	653.2	30.6	14.7	7
Lagocephalus sceleratus	58	127.4	165.8	12.3	2.6	644
Leiognathus bindus	8	3.2	16.3	5.7	1.9	37
Leiognathus elongatus	1	0.1	0.7	6.0	–	1
Leiognathus equulus	1	0.3	3.6	8.0	–	1
Leiognathus leuciscus	4	4.9	36.5	10.1	1.2	48
Leiognathus moretoniensis	13	8.9	46.0	5.7	1.1	130
Leiognathus sp.	40	414.9	3641.2	9.3	2.2	1065
Lepidotrigla argus	19	53.9	166.0	10.8	0.9	211
Lethrinus genivittatus	91	3684.9	4404.5	10.9	2.3	15000
Lethrinus laticaudis	2	9.3	64.0	25.1	6.7	40
Liocranium praepositum	3	1.3	8.3	7.0	1.7	62
Lutjanus carponotatus	1	3.3	36.8	19.8	2.3	8
Lutjanus lutjanus	1	0.1	1.2	7.2	3.3	11
Lutjanus malabaricus	1	1.2	13.4	22.6	19.0	15
Lutjanus quinquelineatus	3	7.3	47.4	8.8	2.8	48
Lutjanus sebae	1	3.7	40.5	18.5	11.5	14
Lutjanus vittus	11	32.0	157.8	15.2	5.2	205
Minous trachycephalus	2	0.5	4.6	6.2	1.8	22
Minous versicolor	5	0.9	4.4	5.7	1.0	33
Monacanthus chinensis	10	4.4	14.4	7.5	2.0	48
Nemipterus furcosus	93	4381.1	3856.0	14.4	3.1	5335
Nemipterus hexodon	26	118.7	347.4	13.4	3.5	232
Nemipterus nematopus	5	18.2	97.9	12.0	2.0	107
Nemipterus peronii	59	290.6	384.8	12.2	2.5	793
Nemipterus sp.	1	2.6	29.0	–	–	–
Nemipterus virgatus	1	4.8	52.8	8.3	0.6	11
Paracentropogon longispinis	27	27.4	126.5	6.2	0.7	385
Paracentropogon vespa	1	0.2	2.4	7.0	–	1
Parachaetodon ocellatus	20	13.3	39.1	8.9	2.2	104
Paramonacanthus choirocephalus	92	568.0	1038.0	6.6	1.1	3810
Paramonacanthus cingalensis	3	4.7	32.1	9.3	0.8	15
Paramonacanthus japonicus	84	249.6	307.5	8.1	1.3	1223
Parapercis nebulosa	11	25.3	83.1	13.1	3.0	61
Parupeneus chryserpleuron	5	9.5	56.9	10.7	2.3	14
Parupeneus heptacanthus	3	5.6	33.8	11.3	2.8	383
Parupeneus indicus	1	8.3	91.6	28.5	–	2
Parupeneus multifasciatus	1	0.8	9.3	7.6	0.5	5
Parupeneus sp.	1	0.2	2.5	6.5	–	2
Pegasus volitans	7	6.1	33.3	11.4	0.9	77
Pelates quadrilineatus	16	231.7	1964.7	10.1	0.8	558
Pellona ditchela	2	3.3	29.5	10.6	2.9	8
Pempheris analis	2	0.4	3.4	8.0	1.3	181
Pentapodus nagasakiensis	2	2.4	15.3	8.6	2.1	654
Pentapodus paradiseus	62	1066.0	2274.8	13.2	2.5	6175
Pentaprion longimanus	17	13.7	39.0	7.0	1.4	127
Platax batavianus	1	1.0	10.5	8.9	8.3	67
Platax teira	9	18.7	65.8	10.7	1.7	13
Platycephalus endrachtensis	2	16.7	113.4	34.8	4.0	13
Platycephalus indicus	1	6.4	71.1	31.0	–	1
Plotosus lineatus	3	4.2	28.5	13.6	4.5	88
Pomacentrus nagasakiensis	2	0.3	2.9	6.7	1.6	135
Priacanthus tayenus	63	675.7	928.1	14.7	2.6	811
Pristotis jerdoni	25	160.6	678.6	6.8	1.5	10000

Species	**%**	**Catch rate ($g h^{-1}$)**	**s.d.**	**Mean size (cm)**	**s.d.**	***n***
Psettodes erumei	1	11.9	131.5	17.7	9.2	9
Pseudalutarius nasicornis	2	4.1	30.4	8.6	1.0	19
Pseudochromis quinquedentatus	2	0.3	2.2	4.9	1.3	45
Pseudocoris yamashiroi	1	1.2	12.9	8.2	0.4	6
Pseudomonacanthus elongatus	2	1.2	7.8	11.2	3.2	44
Pseudomonacanthus peroni	20	67.3	173.6	10.9	5.7	283
Pseudorhombus argus	39	196.0	515.6	14.4	2.1	610
Pseudorhombus arsius	7	28.1	122.3	17.2	2.6	20
Pseudorhombus diplospilus	55	199.8	296.7	16.8	5.4	292
Pseudorhombus dupliciocellatus	22	105.7	287.8	17.2	2.7	170
Pseudorhombus elevatus	19	24.9	104.5	11.2	3.1	113
Pseudorhombus jenynsii	10	23.4	82.9	17.2	2.8	36
Pseudorhombus quinquocellatus	1	1.0	10.6	14.1	3.5	14
Pseudorhombus spinosus	70	364.2	477.3	15.5	2.4	503
Pseudotriacanthus strigilifer	1	0.4	4.0	–	–	–
Pterocaesio digramma	4	15.5	107.7	8.0	3.4	928
Pterois russelli	1	0.8	9.1	11.3	–	4
Pterois volitans	1	0.6	6.7	9.3	–	4
Rhabdamia gracilis	2	0.3	3.1	4.5	0.6	224
Rhynchostracion nasus	60	253.6	399.0	8.0	6.2	775
Sardinella albella	1	0.2	2.6	10.0	–	3
Saurida micropectoralis	16	152.6	522.2	23.0	7.7	86
Saurida undosquamis	92	2061.3	2200.0	19.7	4.8	1565
Scolopsis affinis	5	12.2	65.0	13.2	3.1	177
Scolopsis taeniopterus	72	1451.4	1476.8	11.0	2.7	3017
Scorpaenopsis sp.	1	0.7	7.6	9.0	–	3
Selar boops	8	18.1	66.5	12.0	5.6	73
Selaroides leptolepis	51	185.7	516.3	10.4	3.9	685
Seriolina nigrofasciata	2	14.5	94.1	24.6	2.8	7
Siganus argenteus	3	14.4	107.0	10.7	2.1	22
Siganus canaliculatus	60	268.7	385.2	11.2	2.2	1117
Siganus fuscescens	1	2.5	27.6	12.5	3.1	166
Sillago analis	1	2.1	23.4	15.6	1.5	7
Sillago ingenuua	31	174.0	524.3	14.6	1.5	272
Sillago lutea	1	1.6	17.9	14.5	–	2
Sillago maculata	21	74.9	174.2	15.8	1.6	156
Sillago sihama	1	0.4	3.9	16.7	1.6	30
Siphamia argyrogaster	27	3.9	10.1	4.4	0.8	1696
Siphamia sp.	1	0.1	1.3	4.3	0.7	85
Siphamia versicolor	1	0.1	0.7	3.6	0.6	26
Sirembo imberbis	5	3.9	19.2	16.7	1.7	14
Sorsogona tuberculata	74	175.4	220.9	9.6	1.6	1446
Sphyraena flavicauda	1	1.4	15.4	23.0	–	2
Strabozebrias cancellatus	1	0.9	9.5	21.0	–	2
Suggrundus isacanthus	70	269.4	269.2	14.8	2.9	672
Suggrundus macracanthus	6	4.2	18.9	12.0	4.4	34
Suggrundus rodericensis	1	0.7	8.0	16.5	–	2
Suggrundus sp.2	1	0.3	3.1	10.0	–	1
Suggrundus staigeri	1	2.7	29.5	15.2	6.1	42
Synchiropus rameus	29	59.7	155.1	10.5	1.1	218
Synodus hoshinonis	18	41.7	127.7	11.1	2.2	535
Synodus sageneus	43	113.7	228.0	14.3	3.3	899
Synodus variegatus	2	5.5	39.4	10.3	2.3	324
Tathicarpus butleri	4	0.9	4.5	5.2	1.1	28
Terapon puta	2	2.6	22.6	9.6	1.3	27
Terapon theraps	10	14.6	57.0	10.4	2.9	47
Tetrosomus gibbosus	7	18.9	127.9	12.0	5.9	248
Torquigener hicksi	2	1.3	10.2	9.5	1.8	96
Torquigener pallimaculatus	71	347.2	553.0	8.3	2.1	2163
Torquigener whitleyi	10	21.8	79.1	7.9	1.1	85
Trachinocephalus myops	22	74.6	239.1	13.6	2.9	635

Species	**%**	**Catch rate (g h^{-1})**	**s.d.**	**Mean size (cm)**	**s.d.**	***n***
Tragulichthys jaculiferus	22	78.2	178.8	10.3	5.1	126
Trixiphichthys weberi	2	1.1	9.6	9.8	2.6	16
Upeneus asymmetricus	45	982.5	5712.3	10.3	1.8	2478
Upeneus luzonius	46	202.7	401.2	10.4	3.3	3905
Upeneus moluccensis	7	3.0	11.7	9.4	1.1	15
Upeneus sp.	8	14.0	64.1	8.7	1.9	61
Upeneus sulphureus	3	2.2	12.4	10.2	0.8	14
Upeneus sundaicus	30	178.2	486.7	11.3	1.7	589
Upeneus tragula	74	635.6	720.6	9.8	1.4	3784
Xiphocheilus typus	7	5.0	18.8	10.3	1.1	14
Yongeichthys nebulosus	15	51.5	168.3	11.5	1.4	87
Zabidius novemaculatus	1	13.9	153.5	15.0	–	3
Zebrias craticula	4	4.4	23.3	12.0	1.5	47

Table App.2.B.2 Listing of the percentage occurrence, catch rates and standard deviation of invertebrates collected in the prawn trawl bycatch in the Far Northern Section of the Great Barrier Reef. (n=122 stations).

Species	**%**	**Catch rate ($g\ h^{-1}$)**	**s.d.**
Algae	12	31.2	168.0
Halimeda sp.	2	0.3	2.5
Sponge: Porifera spp.	42	4472.0	16933.6
Cnidaria			
Alcyonarians (mixed spp.)	18	14.5	46.0
Alcyonarian sp.2	2	0.6	4.5
Gorgonacea	36	110.9	410.9
Hydrozoa : Hydroida	12	9.9	44.0
Hydrozoa	9	2.3	9.6
Pennatulacea	7	3.2	15.8
Scleractinia	11	332.1	3224.8
Soft corals	22	657.8	4708.7
Zoantharia	2	0.9	6.3
Zoanthiniaria	1	0.6	6.2
Polychaete tubes empty	2	0.3	2.0
Polychaeta	2	1.6	16.3
Crustaceans	1	0.1	0.7
Alpheidae	3	0.1	0.4
Calappa terraereginae	2	0.3	3.0
Calappidae	2	1.5	11.7
Carid sp.	1	0.0	0.3
Carinosquilla carinata	1	0.3	3.4
Carinosquilla multicarinata	7	3.4	14.9
Charybdis jaubertensis	10	4.6	19.9
Charybdis natator	1	0.8	8.7
Charybdis truncata	30	18.0	39.0
Cryptopodia sp.1	2	0.2	1.3
Dardanus imbricata	1	0.1	0.7
Dorippe frascone	1	0.1	1.7
Dromiidae	2	0.4	2.9
Gonodactylidae	1	0.0	0.2
Gonodactylus graphurus	1	0.1	1.3
Harpiosquilla melanoura	1	0.1	1.0
Heterocrypta sp.1	1	0.1	0.9
Stomatopod sp.	1	0.8	9.0
Hyastenus cambelli	1	0.0	0.4
Hyastenus sp.3	1	0.2	2.1
Isopoda	1	0.0	0.2
Jonas luteanus	1	0.1	0.8
Liagore rubromaculata	1	0.5	5.2
Lupocyclus rotundatus	9	23.1	207.0
Majidae	6	1.1	5.3
Matuta inermis	8	19.4	95.8
Metapenaeopsis palmensis	42	8.3	17.5
Metapenaeopsis sp.	20	2.2	5.3
Metapenaeus sp.	2	0.2	1.3
Metapenaeus endeavouri	11	2.9	10.5
Oratosquilla perpensa	2	1.0	7.4
Oratosquilla quinquedentata	2	1.5	11.6
Oratosquilla woodmasoni	1	0.6	7.0
Paguridae	4	0.5	3.3
Palinuroidea:	28	16.9	34.3
Parthenope hystrix	1	0.1	0.9

Species	**%**	**Catch rate ($g\ h^{-1}$)**	**s.d.**
Panulirus ornatus	2	23.5	212.3
Parthenopidae	1	0.1	0.7
Penaeus esculentus	1	0.2	2.6
Penaeus latisulcatus	1	0.3	2.9
Penaeus longistylus	1	0.5	5.2
Phalangipes australiensis	1	0.0	0.4
Pilumnidae	1	0.0	0.2
Podopthalmus vigil	2	1.9	14.4
Portunidae	2	0.2	1.2
Portunus gracilimanus	22	9.7	23.5
Portunus granulatus	2	0.3	2.0
Portunus pelagicus	33	160.9	333.6
Portunus rubromarginatus	89	1010.1	1459.8
Portunus tenuipes	88	1023.5	1409.0
Scyllarus demani	1	0.1	0.7
Scyllarus sp.	2	0.6	5.6
Scyllarus sp.2	12	7.9	32.0
Sicyonia sp.	1	0.0	0.4
Solenocera pectinata	1	0.0	0.2
Solenoceridae	1	0.0	0.2
Thalamita sima	1	0.4	4.1
Thenus maculata	27	282.0	773.8
Thenus orientalis	57	441.9	683.0
Trachypenaeus anchoralis	9	2.8	13.9
Trachypenaeus fulvus	1	0.3	2.8
Trachypenaeus granulosus	36	7.3	13.6
Trachypenaeus sp.	9	1.2	4.3
Mollusca			
Amusium pleuronectes	7	20.8	101.4
Amusiidae	65	831.8	2205.0
Annachlamys flabellata	30	35.5	78.8
Barbatia foliata	1	0.1	0.7
Bivalvia	15	18.8	143.9
Gastropoda	7	180.2	1506.7
Melaxinia vitrea	1	0.1	1.6
Nudibranchia	5	7.0	68.5
Octopoda	17	52.8	246.5
Opisthobranch	1	0.0	0.2
Ostreidae	5	63.2	592.2
Pitar sp.C	2	1.9	18.4
Placuna lincolni	2	1.6	12.5
Pteria sp.1	2	0.2	1.5
Semele amabilis	1	0.3	3.4
Sepioidae	74	327.6	386.1
Solenidae	2	0.3	2.6
Teuthoidea	33	46.5	146.1
Veneridae	2	0.3	2.6
Bryozoa	5	6.6	50.0
Echinoderms			
Crinoid sp.17	1	0.1	0.9
Crinoidea	33	75.2	231.1
Echinoidea	4	28.7	184.9
Gorgonocephalidae	13	18.8	79.6
Holothurioidea	20	377.9	1995.2
Laganidae	17	8.4	36.0
Spatangoida	9	18.0	133.9
Asteroid (mixed spp.)	23	394.8	1820.4
Ophiuroid (mixed spp.)	5	1.2	6.6
Ascidiacea	11	4.0	14.4

Table App.2.B.3 The frequency of occurrence of species (and classes) of bycatch caught in each stratum and total number caught during the two survey cruises in the Far Northern Section of the Great Barrier Reef, where at least 100 individuals were caught

	PCT OCCURRENCE BYCATCH					
			Stratum			
Class and Species	**A**	**B**	**C**	**D**	**E**	**Total No**
Elasmobranchia						
Dasyatis leylandi	30	28	41	6	22	46
Teleostii	100	100	100	100	100	
Apistus carinatus	70	85	82	29	-	586
Apogon ellioti	88	97	76	24	-	909
Apogon fasciatus	75	100	29	12	-	719
Apogon moluccensis	-	-	12	12	67	256
Apogon nigrocincta	-	-	12	18	44	383
Apogon poecilopterus	35	23	-	-	-	99
Archamia fucata	-	3	6	12	-	183
Callionymus grossi	93	62	71	12	-	447
Canthigaster compressa	3	-	18	35	67	686
Choerodon cephalotes	88	67	53	47	11	451
Choerodon sp	50	69	53	59	-	216
Dactyloptena papilio	50	41	6	6	-	138
Dactylopus dactylopus	50	44	35	24	22	114
Diagramma pictum	53	31	6	6	-	182
Engyprosopon grandisquama	93	72	76	41	22	740
Euristhmus nudiceps	78	97	35	-	-	665
Fistularia petimba	48	77	53	12	-	244
Gerres oyena	48	26	12	6	-	161
Lagocephalus sceleratus	75	74	41	24	11	208
Leiognathus moretoniensis	28	13	-	-	-	145
Leiognathus sp	55	56	24	6	-	1180
Lepidotrigla argus	20	18	35	12	-	111
Lethrinus genivittatus	98	92	65	94	100	5883
Nemipterus furcosus	98	100	94	94	33	3503
Nemipterus hexodon	38	38	12	-	-	131
Nemipterus peronii	80	90	29	-	-	524
Paracentropogon longispinis	30	10	41	53	11	236
Paramonacanthus choirocephalus	95	100	88	94	44	3325
Paramonacanthus japonicus	90	90	71	94	33	873
Pelates quadrilineatus	28	21	-	-	-	601
Pentapodus paradiseus	58	56	65	94	44	1343
Pentaprion longimanus	25	26	6	-	-	108
Priacanthus tayenus	80	97	29	6	11	480
Pristotis jerdoni	25	15	24	24	78	508
Pseudorhombus argus	38	18	82	65	11	242
Pseudorhombus diplospilus	73	72	53	-	11	217
Pseudorhombus dupliciocellatus	13	33	41	12	-	106
Pseudorhombus spinosus	88	77	76	41	11	469
Rhynchostracion nasus	85	74	47	12	-	556
Saurida undosquamis	98	100	88	88	44	1343
Scolopsis taeniopterus	98	100	59	-	-	2712
Selaroides leptolepis	68	67	47	6	-	275

PCT OCCURRENCE BYCATCH

			Stratum			
Class and Species	**A**	**B**	**C**	**D**	**E**	**Total No**
Siganus canaliculatus	85	82	35	6	-	444
Sillago ingenuua	40	23	18	41	33	275
Sorsogona tuberculata	60	90	94	76	22	672
Suggrundus isacanthus	95	90	65	12	-	420
Synchiropus rameus	43	36	24	-	-	161
Synodus hoshinonis	3	15	41	47	-	100
Synodus sageneus	50	46	41	29	22	149
Torquigener pallimaculatus	78	79	88	59	-	665
Trachinocephalus myops	8	10	24	65	56	100
Upeneus asymmetricus	60	54	18	24	33	1642
Upeneus luzonius	60	36	29	53	44	334
Upeneus sundaicus	55	31	12	-	-	360
Upeneus tragula	93	87	59	35	33	1810
Algae	8	3	12	35	56	
Panfera	53	38	47	18	44	
Hydrozoa	35	10	12	29	11	
Pennatulacea	8	3	6	-	33	
Gorgoncea	48	38	18	18	44	
Zoantharia	10	5	18	12	67	
Alcyonacea	38	38	24	53	78	
Crustacea	100	100	100	100	100	
Metapenaeopsis palmensis	30	33	59	65	56	230
Metapenaeopsis sp	25	36	6	-	-	105
Palinuroidea: SCYLLARIDAE	43	21	53	-	-	108
Portunus rubromarginatus	100	97	94	71	33	2611
Portunus tenuipes	95	97	88	71	44	4945
Thenus maculata	18	13	53	53	33	100
Thenus orientalis	80	72	41	12	-	253
Trachypenaeus granulosus	35	62	29	-	11	272
Gastropoda	3	3	24	18	56	
Bivalvia	95	100	76	18	44	
Amussiidae	83	100	41	-	-	4501
Annachlamys flabellata	38	49	18	-	-	136
Ostreidae	-	-	6	12	33	964
Cephalopoda	85	92	100	65	89	
Sepioidae	80	79	94	47	33	388
Teuthoidea	38	21	41	24	67	100
Bryozoan	3	-	6	12	22	
Crinoid	20	15	41	71	89	
Asteroid	45	28	47	24	44	
Echinoid	15	18	6	-	22	
Ophiuroid	10	10	41	29	33	
Holothurian	15	23	12	12	56	
Ascidian	8	5	24	29	-	

Table App.2.B.4 The mean biomass of species (and classes) of bycatch caught in each stratum and total number caught during the two survey cruises in the Far Northern Section of the Great Barrier Reef, where at least 100 individuals were caught.

	MEAN WEIGHT OVERALL PER STN IN KGS					
			Stratum			
Class and Species	**A**	**B**	**C**	**D**	**E**	**Total No.**
Elasmobranchia						
Dasyatis leylandi	0.05	0.03	0.09	0.03	0.08	46
Teleostii	12.69	14.56	12.23	9.85	5.73	
Apistus carinatus	0.13	0.11	0.14	0.02	0.00	586
Apogon ellioti	0.12	0.18	0.10	0.00	0.00	909
Apogon fasciatus	0.08	0.07	0.01	0.00	0.00	719
Apogon moluccensis	0.00	0.00	0.00	0.01	0.15	256
Apogon nigrocincta	0.00	0.00	0.00	0.00	0.17	383
Apogon poecilopterus	0.02	0.02	0.00	0.00	0.00	99
Archamia fucata	0.00	0.00	0.00	0.05	0.00	183
Callionymus grossi	0.16	0.06	0.09	0.01	0.00	447
Canthigaster compressa	0.00	0.00	0.06	0.29	0.04	686
Choerodon cephalotes	0.30	0.21	0.28	0.12	0.03	451
Choerodon sp	0.03	0.07	0.09	0.07	0.00	216
Dactyloptena papilio	0.03	0.02	0.00	0.02	0.00	138
Dactylopus dactylopus	0.03	0.02	0.02	0.01	0.01	114
Diagramma pictum	0.09	0.02	0.01	0.01	0.00	182
Engyprosopon grandisquama	0.08	0.04	0.24	0.06	0.01	740
Euristhmus nudiceps	0.20	0.45	0.04	0.00	0.00	665
Fistularia petimba	0.04	0.05	0.05	0.01	0.00	244
Gerres oyena	0.10	0.04	0.01	0.00	0.00	161
Lagocephalus sceleratus	0.08	0.09	0.04	0.03	0.01	208
Leiognathus moretoniensis	0.01	0.00	0.00	0.00	0.00	145
Leiognathus sp	0.57	0.06	0.01	0.00	0.00	1180
Lepidotrigla argus	0.03	0.02	0.08	0.01	0.00	111
Lethrinus genivittatus	1.63	2.06	0.82	3.07	1.46	5883
Nemipterus furcosus	2.11	3.05	2.84	0.71	0.39	3503
Nemipterus hexodon	0.04	0.13	0.02	0.00	0.00	131
Nemipterus peronii	0.22	0.18	0.11	0.00	0.00	524
Paracentropogon longispinis	0.01	0.00	0.05	0.02	0.00	236
Paramonacanthus choirocephalus	0.55	0.19	0.12	0.19	0.01	3325
Paramonacanthus japonicus	0.15	0.11	0.10	0.20	0.01	873
Pelates quadrilineatus	0.07	0.29	0.00	0.00	0.00	601
Pentapodus paradiseus	0.20	0.57	1.32	0.63	0.18	1343
Pentaprion longimanus	0.01	0.01	0.00	0.00	0.00	108
Priacanthus tayenus	0.28	0.70	0.14	0.00	0.01	480
Pristotis jerdoni	0.01	0.00	0.04	0.18	0.59	508
Pseudorhombus argus	0.03	0.01	0.40	0.20	0.00	242
Pseudorhombus diplospilus	0.14	0.13	0.08	0.00	0.02	217
Pseudorhombus dupliciocellatus	0.01	0.05	0.20	0.02	0.00	106
Pseudorhombus spinosus	0.23	0.11	0.37	0.15	0.01	469
Rhynchostracion nasus	0.17	0.16	0.15	0.00	0.00	556
Saurida undosquamis	0.82	0.84	1.26	1.91	0.69	1343

MEAN WEIGHT OVERALL PER STN IN KGS

	Stratum					
Class and Species	**A**	**B**	**C**	**D**	**E**	**Total No.**
Scolopsis taeniopterus	0.96	1.08	0.45	0.00	0.00	2712
Selaroides leptolepis	0.06	0.17	0.14	0.01	0.00	275
Siganus canaliculatus	0.20	0.16	0.10	0.03	0.00	444
Sillago ingenuua	0.16	0.01	0.03	0.14	0.08	275
Sorsogona tuberculata	0.04	0.10	0.19	0.08	0.04	672
Suggrundus isacanthus	0.18	0.17	0.14	0.01	0.00	420
Synchiropus rameus	0.06	0.03	0.02	0.00	0.00	161
Synodus hoshinonis	0.00	0.00	0.08	0.06	0.00	100
Synodus sageneus	0.08	0.05	0.06	0.03	0.04	149
Torquigener pallimaculatus	0.14	0.19	0.32	0.16	0.00	665
Trachinocephalus myops	0.00	0.00	0.03	0.18	0.09	100
Upeneus asymmetricus	0.37	0.98	0.12	0.23	0.09	1642
Upeneus luzonius	0.13	0.04	0.05	0.18	0.21	334
Upeneus sundaicus	0.20	0.06	0.02	0.00	0.00	360
Upeneus tragula	0.40	0.46	0.13	0.12	0.04	1810
Algae	0.00	0.00	0.00	0.06	0.10	
Panfera	4.88	0.73	2.84	0.02	0.07	
Hydrozoa	0.02	0.00	0.00	0.00	0.00	
Pennatulacea	0.00	0.00	0.00	0.00	0.01	
Gorgonacea	0.11	0.01	0.08	0.01	0.06	
Zoantharia	0.02	0.00	0.01	0.00	2.11	
Alcyonacea	0.03	0.03	0.01	0.09	4.16	
Crustacea	1.28	1.18	3.67	1.57	0.22	
Metapenaeopsis palmensis	0.00	0.00	0.01	0.01	0.00	230
Metapenaeopsis sp	0.00	0.00	0.00	0.00	0.00	105
Palinuroidea: Scyllaridae	0.02	0.00	0.01	0.00	0.00	108
Portunus rubromarginatus	0.33	0.32	1.43	0.67	0.04	2611
Portunus tenuipes	0.40	0.49	1.39	0.21	0.01	4945
Thenus maculata	0.02	0.01	0.37	0.49	0.13	100
Thenus orientalis	0.28	0.25	0.25	0.09	0.00	253
Trachypenaeus granulosus	0.00	0.01	0.01	0.00	0.00	272
Gastropodea	0.00	0.00	0.18	0.03	0.88	
Bivalve	0.56	0.83	0.06	0.03	0.38	
Amussiidae	0.51	0.76	0.04	0.00	0.00	4501
Annachlamys flabellata	0.02	0.03	0.01	0.00	0.00	136
Ostreidae	0.00	0.00	0.00	0.02	0.38	964
Cephalopoda	0.24	0.19	0.30	0.14	0.19	
Sepioidae	0.22	0.14	0.26	0.08	0.01	388
Teuthoidea	0.02	0.02	0.01	0.02	0.06	100
Bryozoa	0.00	0.00	0.00	0.02	0.00	
Crinoid	0.00	0.01	0.03	0.11	0.19	
Asteroid	0.11	0.00	1.16	0.02	0.00	
Echinoid	0.04	0.01	0.00	0.00	0.11	
Holothurian	0.02	0.01	0.07	0.41	1.56	
Ophiuroid	0.00	0.00	0.01	0.01	0.07	
Ascidian	0.00	0.00	0.00	0.01	0.00	

Table App.2.B.5 The mean number of bycatch animals caught at each station in each stratum during the two survey cruises in the Far Northern Section of the Great Barrier Reef, where at least 100 individuals were caught.

	MEAN NUMBER PER STATION					
			Stratum			
Class and Species	**A**	**B**	**C**	**D**	**E**	**Total No**
Elasmobranchia						
Dasyatis leylandi	0	0	1	0	0	46
Teleostii	447	333	278	262	229	
Apistus carinatus	6	5	7	1	0	586
Apogon ellioti	10	9	9	1	0	909
Apogon fasciatus	9	9	1	0	0	719
Apogon moluccensis	0	0	0	1	26	256
Apogon nigrocincta	0	0	1	0	40	383
Apogon poecilopterus	1	1	0	0	0	99
Archamia fucata	0	0	0	10	0	183
Callionymus grossi	8	2	3	0	0	447
Canthigaster compressa	0	0	6	32	3	686
Choerodon cephalotes	6	3	4	2	0	451
Choerodon sp	1	2	3	2	0	216
Dactyloptena papilio	2	1	0	0	0	138
Dactylopus dactylopus	1	1	1	0	0	114
Diagramma pictum	4	1	0	0	0	182
Engyprosopon grandisquama	6	3	18	4	1	740
Euristhmus nudiceps	5	12	1	0	0	665
Fistularia petimba	2	3	3	0	0	244
Gerres oyena	3	1	0	0	0	161
Lagocephalus sceleratus	2	2	1	1	0	208
Leiognathus moretoniensis	3	0	0	0	0	145
Leiognathus sp	26	3	0	0	0	1180
Lepidotrigla argus	1	1	3	0	0	111
Lethrinus genivittatus	47	51	21	79	37	5883
Nemipterus furcosus	33	36	33	10	5	3503
Nemipterus hexodon	1	2	1	0	0	131
Nemipterus peronii	8	5	2	0	0	524
Paracentropogon longispinis	1	0	7	3	0	236
Paramonacanthus choirocephalus	60	15	7	11	1	3325
Paramonacanthus japonicus	11	6	5	8	0	873
Pelates quadrilineatus	4	11	0	0	0	601
Pentapodus paradiseus	6	12	23	12	4	1343
Pentaprion longimanus	2	1	0	0	0	108
Priacanthus tayenus	4	8	1	0	0	480
Pristotis jerdoni	1	0	2	9	29	508
Pseudorhombus argus	1	0	8	4	0	242
Pseudorhombus diplospilus	2	3	1	0	0	217
Pseudorhombus dupliciocellatus	0	1	3	0	0	106
Pseudorhombus spinosus	5	3	8	2	0	469
Rhynchostracion nasus	9	4	2	0	0	556
Saurida undosquamis	11	10	13	13	5	1343
Scolopsis taeniopterus	42	22	9	0	0	2712
Selaroides leptolepis	2	4	3	0	0	275
Siganus canaliculatus	6	4	2	1	0	444

	MEAN NUMBER PER STATION					
			Stratum			
Class and Species	**A**	**B**	**C**	**D**	**E**	**Total No**
Sillago ingenuua	5	0	0	3	2	275
Sorsogona tuberculata	3	5	15	6	3	672
Suggrundus isacanthus	5	4	3	0	0	420
Synchiropus rameus	3	1	1	0	0	161
Synodus hoshinonis	0	0	2	3	0	100
Synodus sageneus	2	1	2	1	1	149
Torquigener pallimaculatus	7	5	8	4	0	665
Trachinocephalus myops	0	0	1	3	3	100
Upeneus asymmetricus	12	25	3	7	3	1642
Upeneus luzonius	4	1	1	4	5	334
Upeneus sundaicus	7	1	0	0	0	360
Upeneus tragula	21	20	5	6	3	1810
Algae	0	0	0	0	1	
Panfera	1	1	1	0	1	
Hydrozoan	0	0	0	0	0	
Pennatulacea	0	0	0	0	1	
Gorgonacea	1	0	0	0	1	
Zoantharia	0	0	1	0	1	
Alcyonacea	1	0	1	2	3	
Crustacea	62	69	187	51	8	
Metapenaeopsis palmensis	1	2	3	2	2	230
Metapenaeopsis sp	1	2	0	0	0	105
Palinuroidea: SCYLLARIDAE	2	0	1	0	0	108
Portunus rubromarginatus	17	14	57	25	2	2611
Portunus tenuipes	30	39	112	17	1	4945
Thenus maculata	0	0	2	2	1	100
Thenus orientalis	3	3	2	0	0	253
Trachypenaeus granulosus	2	4	2	0	0	272
Gastropod	0	0	1	1	1	
Bivalvia	48	71	4	4	99	
Amussiidae	45	68	3	0	0	4501
Annachlamys flabellata	1	2	1	0	0	136
Ostreidae	0	0	0	4	99	964
Cephalopoda	5	3	6	2	4	
Sepioidae	5	3	4	1	0	388
Teuthoidea	1	0	2	1	3	100
Bryozoan	0	0	0	0	0	
Crinoid	0	0	1	4	19	
Asteroid	1	0	1	1	1	
Echinoid	2	1	0	0	0	
Holothurian	0	0	1	0	1	
Ophiuroid	0	0	1	1	1	
Ascidian	0	0	1	2	0	

APPENDIX.2.C

Table App.2.C.1 Listing of the percentage occurrence, catch rate, standard deviation, mean size and standard deviation and the number of fish measured from fish trawl catches in the Far Northern Section of the Great Barrier Reef (n = 152 stations).

Species	%	Catch rate ($g\ h^{-1}$)	s.d.	Mean size (cm)	s.d.	*n*
Elasmobranchs						
Amphotistius kuhlii	6	393.2	2449.5	31.3	4.8	63
Carcharhinus brachyurus	1	87.2	1065.0	115.0	–	1
Carcharhinus brevipinna	1	22.8	278.5	80.0	–	1
Carcharhinus dussumieri	5	398.7	1939.0	79.7	3.8	11
Carcharhinus limbatus	5	580.2	3397.3	75.1	11.8	18
Dasyatis fluviorum	1	402.7	4915.4	90.0	–	1
Dasyatis leylandi	6	53.9	299.8	21.8	5.5	46
Dasyatis thetidis	2	3551.3	33900.1	130.0	–	4
Galeocerdo cuvier	1	47.0	573.5	130.7	–	3
Gymnura australis	7	339.8	1379.0	52.4	9.6	17
Hemigaleus microstoma	3	88.3	629.8	64.8	13.2	6
Hemipristis elongata	3	760.6	5009.9	154.8	–	4
Himantura fai	1	1476.5	15084.3	160.0	–	2
Himantura granulata	1	201.3	2457.7	110.0	–	2
Himantura toshi	7	1193.5	7774.8	61.1	16.0	15
Himantura uarnak	1	37.3	454.8	60.3	–	4
Nebrius concolor	3	4429.5	25023.8	233.7	37.3	12
Rhina ancylostoma	1	536.9	6553.9	148.5	–	2
Rhizoprionodon acutus	12	742.1	2384.4	76.7	10.8	32
Rhynchobatus djiddensis	4	655.7	4227.9	97.8	33.8	10
Sphyrna lewini	2	339.9	3361.8	95.3	–	3
Stegostoma fasciatum	3	1369.1	8798.3	178.0	27.4	7
Teleostii						
Apogonidae	3	2.5	18.2	5.1	0.6	58
Balistidae	1	0.7	8.5	8.7	–	3
Carapidae	1	0.2	1.7	15.0	–	1
Engraulididae	1	0.7	8.2	10.0	–	1
Gerreidae	1	12.0	136.7	12.5	–	2
Labridae	5	4.1	28.2	8.8	1.0	18
Lethrinidae	1	7.5	76.1	13.3	–	3
Mullidae	3	4.2	31.2	8.1	1.9	25
Muraenidae	1	0.9	10.4	24.0	–	1
Pomacentridae	1	0.1	1.3	6.0	–	1
Synodontidae	1	0.2	2.4	8.3	–	3
Abalistes stellaris	12	1197.6	6075.3	27.9	8.0	204
Acanthurus grammoptilus	1	15.9	194.0	20.3	5.1	10
Acentrogobius caninus	1	0.5	5.8	10.0	–	1
Aetobatus narinari	1	335.6	4096.2	161.8	10.3	5
Aetomylaeus vespertilio	1	536.9	6553.9	183.0	–	2
Alectis ciliaris	1	0.8	9.6	12.4	3.9	10
Alectis indicus	3	17.8	127.4	13.8	–	4
Alepes sp.	27	1536.5	5906.9	19.8	2.3	224
Amblygaster sirm	3	14.6	131.9	15.6	3.2	15
Anacanthus barbatus	2	1.0	8.5	22.9	4.3	7
Anampses twistii	1	1.2	14.3	15.0	–	1
Anchisomus multistriatus	1	16.1	196.6	19.7	16.9	6
Apistus carinatus	2	2.8	22.1	9.7	–	3
Apogon ellioti	1	0.2	2.9	8.0	–	2

Species	%	**Catch rate** (g h^{-1})	**s.d.**	**Mean size** (cm)	**s.d.**	*n*
Apogon fasciatus	7	25.6	123.0	7.5	1.0	62
Apogon septemstriatus	1	0.1	0.8	6.0	–	1
Aprion virescens	1	69.8	852.0	74.0	–	2
Arius thalassinus	1	2.8	33.9	15.0	–	1
Arothron aerostaticus	2	8.7	68.1	10.7	–	3
Arothron hispidus	2	29.0	314.7	11.5	10.4	17
Arothron manillensis	1	1.4	16.8	7.5	–	2
Atule mate	9	235.5	1415.1	21.8	5.3	48
Balistoides viridescens	2	127.6	952.0	39.2	7.8	6
Caesio caerulaurea	1	1.0	11.8	10.0	–	2
Callionymus grossi	1	0.8	9.8	13.0	–	1
Canthigaster compressa	17	91.6	493.3	5.4	0.7	870
Canthigaster rivulata	1	1.2	13.2	5.9	1.1	14
Canthigaster valentini	1	0.3	3.9	7.5	–	2
Carangoides caeruleopinnatus	23	694.8	1927.5	16.3	3.4	141
Carangoides chrysophrys	11	260.4	1025.4	16.4	8.0	89
Carangoides fulvoguttatus	17	160.3	529.2	18.6	4.6	119
Carangoides gymnostethus	27	280.1	803.4	17.5	5.5	187
Carangoides hedlandensis	31	1070.5	2827.5	13.8	3.1	176
Carangoides humerosus	27	563.2	1453.7	18.9	4.0	87
Carangoides malabaricus	4	73.9	595.4	17.2	2.2	30
Carangoides talamparoides	12	225.1	961.1	14.0	2.6	71
Caranx bucculentus	19	5163.2	26649.9	14.5	3.6	517
Caranx ignobilis	1	2.7	32.6	17.0	–	1
Centriscus scutatus	13	24.2	108.8	15.5	2.6	250
Chaetoderma penicilligera	1	0.3	4.1	10.6	3.2	15
Chaetodon kleinii	1	0.4	5.2	9.0	–	1
Chaetodontoplus duboulayi	9	142.1	676.8	13.5	3.3	177
Cheilinus chlorourus	1	2.2	27.0	17.0	–	1
Chelmon marginalis	2	18.8	178.3	12.6	1.7	37
Chirocentrus dorab	2	81.9	738.3	41.1	4.8	8
Choerodon cephalotes	46	896.0	2436.1	14.1	3.2	369
Choerodon monostigma	12	61.5	224.3	11.7	1.6	33
Choerodon schoenleinii	5	891.3	4863.1	47.5	9.3	117
Choerodon sp.2	55	457.3	728.6	10.9	1.7	751
Choerodon vitta	4	28.7	165.3	12.9	3.0	67
Coradion chrysozonus	9	12.8	58.3	8.1	2.3	182
Ctenotrypauchen sp.	1	0.2	2.8	7.8	–	4
Cybiosarda elegans	1	57.9	510.1	31.3	–	3
Cymolutes torquatus	1	0.6	5.3	12.4	0.9	5
Cyprinocirrhites polyactis	1	0.1	1.2	5.0	–	1
Dactyloptena papilio	1	1.1	14.0	8.0	–	1
Decapterus macrosoma	1	14.6	166.0	18.3	3.2	12
Decapterus russellii	20	399.7	1699.4	14.1	2.1	253
Dendrochirus brachypterus	1	0.2	2.6	6.0	–	1
Dendrochirus zebra	1	2.4	29.2	14.0	–	2
Diagramma pictum	32	7101.3	19472.9	45.5	17.6	846
Dussumieria acuta	1	9.5	115.6	12.1	1.8	7
Dussumieria elopsoides	18	672.7	2981.7	15.5	0.7	252
Echeneis naucrates	22	503.7	1157.6	46.0	12.5	105
Encrasicholina heterolobus	1	0.1	0.7	5.0	–	1
Epigonus lenimen	1	51.1	623.3	–	–	–
Epinephelus coioides	1	338.3	2962.7	78.0	–	2
Epinephelus tauvina	3	636.2	4209.6	72.8	–	4
Fistularia commersonii	5	35.3	206.6	44.1	12.5	50
Fistularia petimba	51	297.7	471.5	32.6	3.8	615
Gazza minuta	16	1018.4	10330.7	10.4	1.3	201
Gerres filamentosus	3	71.8	800.3	10.2	0.8	47
Gerres oyena	35	898.9	2877.7	11.9	1.7	528
Gerres subfasciatus	1	14.5	156.3	11.1	1.2	18
Glaucosoma magnificum	14	459.2	3744.1	10.1	1.3	418
Gnathanodon speciosus	17	2512.5	18042.4	17.8	17.5	246

Species	%	Catch rate (g h^{-1})	s.d.	Mean size (cm)	s.d.	*n*
Gymnocranius elongatus	1	1.5	14.3	10.0	–	1
Gymnocranius griseus	1	2.1	25.1	12.5	–	2
Halichoeres zeylonicus	2	6.6	59.9	15.0	2.0	22
Herklotsichthys koningsbergeri	1	61.3	711.9	13.5	1.0	6
Herklotsichthys lippa	22	343.6	1201.5	11.4	1.7	327
Lactoria cornuta	7	79.1	478.9	18.8	3.3	62
Lagocephalus lunaris	7	304.7	1322.5	38.8	10.3	13
Lagocephalus sceleratus	39	311.2	947.6	11.8	4.3	261
Lagocephalus spadiceus	2	41.1	389.0	12.2	1.7	13
Leiognathus bindus	49	5354.1	15999.9	7.2	1.3	3382
Leiognathus equulus	3	14.4	116.7	8.3	0.5	12
Leiognathus leuciscus	21	200.4	640.5	8.7	1.4	272
Leiognathus moretoniensis	5	6.2	39.1	6.3	0.6	35
Leiognathus smithursti	3	56.8	522.3	9.8	0.5	48
Leiognathus sp.	62	35633.2	61297.5	9.6	1.6	7686
Lethrinus genivittatus	93	27465.2	50051.1	11.9	1.9	14000
Lethrinus laticaudis	14	1655.1	6820.9	29.3	6.6	499
Lethrinus lentjan	1	21.4	212.0	29.1	3.3	16
Lethrinus nebulosus	4	532.9	3737.2	49.0	7.8	14
Lethrinus rubrioperculatus	1	15.1	144.3	18.5	3.5	6
Lethrinus variegatus	2	49.7	561.4	16.4	3.2	26
Lutjanus carponotatus	1	48.6	418.2	25.6	3.0	5
Lutjanus erythropterus	1	40.8	498.3	22.7	–	3
Lutjanus kasmira	1	1.9	22.8	16.0	–	1
Lutjanus lutjanus	1	146.9	1793.0	15.1	1.0	105
Lutjanus malabaricus	7	920.5	5278.7	53.3	23.3	33
Lutjanus russelli	2	35.6	250.9	30.7	5.2	6
Lutjanus sebae	13	1747.4	7340.2	45.2	20.2	104
Lutjanus vittus	19	1368.8	5475.5	17.9	4.0	559
Megalaspis cordyla	2	14.6	141.2	12.7	–	3
Megalops cyprinoides	1	79.2	966.7	40.8	3.0	5
Mene maculata	13	1700.0	8852.5	12.3	1.1	468
Monotaxis grandoculis	1	116.8	1075.3	38.4	8.6	5
Naso annulatus	3	20.5	163.0	17.2	7.7	10
Naso fageni	1	1.1	13.3	14.0	–	1
Nemipterus furcosus	85	9583.1	13510.4	15.9	2.5	3070
Nemipterus hexodon	23	380.3	1233.2	14.5	3.6	106
Nemipterus nematopus	6	135.0	773.6	16.3	1.6	29
Nemipterus peronii	23	162.2	419.2	15.6	3.0	189
Odonus niger	1	5.0	60.5	22.0	–	1
Ostracion cubicus	3	89.3	676.8	22.0	4.4	40
Parachaetodon ocellatus	10	50.4	204.8	11.7	2.7	75
Paramonacanthus choirocephalus	12	13.9	51.6	7.6	0.7	51
Paramonacanthus japonicus	33	82.8	190.5	8.1	1.5	141
Parapercis nebulosa	2	3.2	25.4	14.3	–	3
Parastromateus niger	2	51.7	374.3	16.5	4.4	14
Parupeneus chryserpleuron	3	33.0	301.4	11.0	1.9	75
Parupeneus heptacanthus	11	183.4	946.2	12.8	3.4	466
Parupeneus indicus	1	14.1	172.7	23.5	3.8	22
Pelates quadrilineatus	7	2543.4	19691.1	10.1	0.6	579
Pellona ditchela	3	3553.9	42671.7	14.2	0.7	115
Pentapodus nagasakiensis	5	26.0	194.4	7.6	1.7	442
Pentapodus paradiseus	65	6170.1	19374.4	14.4	2.0	7271
Pentaprion longimanus	26	710.9	3604.9	8.3	1.1	657
Platax batavianus	13	2601.3	9946.2	41.2	11.4	179
Platax teira	10	54.7	217.7	10.8	2.3	25
Platycephalus endrachtensis	1	13.8	126.1	36.4	3.6	5
Plectropomus maculatus	4	196.7	1316.9	40.1	13.3	20
Plotosus lineatus	7	60.8	468.5	12.0	2.6	149
Pomacanthus sexstriatus	1	17.1	208.9	28.1	4.9	8
Priacanthus tayenus	39	1206.3	3991.5	16.3	3.1	236
Pristotis jerdoni	29	859.3	3116.7	7.0	1.4	6023

Species	%	Catch rate (g h^{-1})	s.d.	Mean size (cm)	s.d.	*n*
Pseudalutarius nasicornis	5	13.2	106.6	7.9	1.3	111
Pseudochromis quinquedentatus	1	0.3	2.7	6.0	–	2
Pseudomonacanthus elongatus	1	0.8	7.3	12.0	2.1	8
Pseudomonacanthus peroni	7	50.7	210.6	16.1	6.1	44
Pseudorhombus argus	3	6.7	46.0	15.4	1.5	31
Pseudorhombus diplospilus	4	35.4	196.1	22.4	4.0	12
Pseudorhombus dupliciocellatus	1	4.7	57.6	22.0	–	1
Pseudorhombus elevatus	1	1.0	12.4	10.0	–	1
Pseudorhombus jenynsii	1	4.9	59.8	17.0	–	1
Pseudorhombus spinosus	3	13.6	76.1	17.0	1.2	5
Pterocaesio digramma	6	363.5	2010.6	11.1	3.6	827
Pterocaesio marri	1	0.9	10.8	13.0	–	2
Rachycentron canadum	5	4244.1	49938.1	72.7	29.7	45
Rastrelliger kanagurta	27	875.2	2963.9	17.5	1.7	206
Rhabdamia cypselurus	1	0.7	8.0	5.4	0.6	17
Rhynchostracion nasus	11	229.2	1048.8	23.9	6.7	43
Rhynchostracion rhinorhynchus	1	85.7	908.6	34.3	–	3
Sardinella albella	3	17.2	114.7	11.1	1.0	15
Sardinella gibbosa	1	4.7	44.0	12.8	0.9	8
Saurida gracilis	1	1.3	15.5	13.7	–	3
Saurida micropectoralis	13	424.4	1367.0	25.4	5.4	56
Saurida sp.2	1	3.4	41.9	22.0	5.7	5
Saurida undosquamis	75	2446.0	4563.4	18.6	4.7	874
Scarus ghobban	3	292.5	1979.7	38.1	7.3	51
Scolopsis affinis	11	313.3	1551.3	14.1	2.6	454
Scolopsis monogramma	2	44.9	315.5	18.9	5.7	54
Scolopsis taeniopterus	37	1432.1	10535.7	14.8	2.9	280
Scomberoides commersonnianus	1	107.9	1231.5	44.3	–	3
Scomberoides tol	4	172.6	1286.5	26.0	5.6	20
Scomberomorus commerson	7	393.8	1980.5	41.6	12.5	26
Scomberomorus munroi	8	346.8	1764.7	44.4	7.8	26
Scomberomorus queenslandicus	45	4486.5	13030.0	36.9	11.4	283
Scomberomorus semifasciatus	7	796.0	3879.1	58.7	14.0	20
Secutor insidiator	7	50.9	453.9	7.9	0.7	72
Secutor ruconius	1	0.8	10.2	9.0	–	1
Selar boops	37	6686.7	22656.0	14.7	2.1	1330
Selar crumenophthalmus	5	117.3	614.6	15.4	3.5	55
Selaroides leptolepis	75	39354.8	70812.6	12.3	1.8	10000
Seriolina nigrofasciata	15	614.7	1837.8	25.2	4.4	29
Siganus canaliculatus	71	4340.1	7822.9	13.0	1.8	3461
Siganus fuscescens	5	166.2	1290.6	13.6	3.9	673
Siganus punctatus	1	29.3	357.8	27.0	–	1
Sillago ingenuua	3	21.1	162.2	15.4	1.3	30
Sillago maculata	10	266.9	1340.5	16.4	2.2	83
Sillago sihama	1	7.3	63.9	15.2	1.2	10
Sorsogona tuberculata	1	0.2	2.1	8.5	–	2
Sphyraena flavicauda	16	3227.6	22789.4	21.8	2.0	503
Sphyraena forsteri	23	576.1	1973.0	21.1	2.6	112
Sphyraena putnamiae	2	28.2	268.4	29.5	–	4
Spratelloides lewisi	1	0.2	1.7	5.0	–	3
Stolephorus devisi	1	0.5	5.6	5.0	–	3
Stolephorus indicus	3	16.9	154.0	12.3	0.7	22
Sufflamen chrysopterus	1	1.0	11.8	11.0	–	1
Sufflamen fraenatus	3	27.4	181.1	24.0	–	4
Suggrundus isacanthus	1	5.6	48.0	17.5	–	2
Suggrundus macracanthus	1	1.1	14.0	18.0	–	1
Symphorus nematophorus	4	865.8	4733.6	60.7	14.1	26
Synodus hoshinonis	6	6.6	29.0	13.4	1.5	20
Synodus jaculum	1	0.6	5.2	11.3	1.7	31
Synodus sageneus	11	35.8	134.3	14.6	2.2	98
Synodus variegatus	1	0.0	0.6	10.9	1.8	92
Terapon puta	1	9.5	94.8	10.9	0.7	10

Species	%	Catch rate (g h^{-1})	s.d.	Mean size (cm)	s.d.	*n*
Terapon theraps	5	242.2	1487.4	13.8	1.8	53
Tetrosomus gibbosus	10	219.7	903.9	17.5	2.6	235
Torquigener brevipinnis	3	1.2	7.7	8.0	0.7	5
Torquigener hicksi	1	5.7	54.5	11.6	2.2	14
Torquigener pallimaculatus	51	848.6	2043.9	10.1	2.2	550
Torquigener whitleyi	5	28.7	167.9	8.4	1.6	28
Trachinocephalus myops	9	12.9	47.8	13.3	2.7	106
Tragulichthys jaculiferus	5	72.2	391.3	15.3	4.7	24
Trichiurus lepturus	1	3.0	27.6	36.5	–	2
Trixiphichthys weberi	1	0.8	9.8	10.5	–	2
Ulua aurochs	1	14.6	138.4	15.0	–	3
Upeneus asymmetricus	20	948.0	7477.5	11.1	1.6	599
Upeneus luzonius	29	781.4	3100.1	11.9	2.7	1135
Upeneus moluccensis	6	23.9	131.8	8.8	1.0	43
Upeneus sp.	3	49.3	358.5	12.3	1.6	14
Upeneus sulphureus	8	44.4	244.9	9.6	0.6	35
Upeneus sundaicus	16	406.4	1481.0	11.4	1.3	334
Upeneus tragula	23	209.0	1093.9	10.3	1.2	246
Uraspis uraspis	8	158.6	928.5	15.6	2.8	21
Xiphocheilus typus	3	5.7	36.6	11.0	2.7	6
Xyrichtys jacksonensis	1	1.0	12.6	13.7	3.1	12
Xyrichtys pavo	1	0.8	9.2	13.0	–	1
Yongeichthys nebulosus	1	1.5	17.9	13.0	–	1
Zabidius novemaculatus	1	38.2	372.4	20.5	–	2

Table App.2.C.2 Listing of the percentage of occurrence, catch rate and standard deviation of benthic invertebrate species/taxa measured from fish trawl catches in the Far Northern Section of the Great Barrier Reef (n = 122stations).

Species/Taxa	%	Catch Rate (gh^{-1})	s.d.
Algae	6	4.8	28.9
Chlorophyceae	1	0.2	2.4
Halimeda sp	1	26.8	230.9
Sponge: Porifera	38	5845.3	17551.5
Acropora sp.	3	512.8	5010.0
Alcyonacea - Dendronephthya	2	8.2	73.1
Cnidarian: Coelenterate	1	301.1	3513.7
Gorgonacea	14	396.1	3399.7
Hydroid: Hydrozoa	9	6.4	38.3
Pennatulacea	1	2.7	23.1
Scleractinia	11	451.8	4533.2
Alcyonacea - Sarcophyton	5	20.0	150.4
Charybdis jaubertensis	1	0.2	2.8
Hyastenus sp. 3	3	25.7	236.3
Majidae	1	1.4	16.9
Palinuroidea	1	0.3	2.9
Panulirus ornatus	1	23.8	234.9
Parthenopidae	1	0.1	0.8
Portunus pelagicus	1	1.3	16.4
Portunus rubromarginatus	2	0.8	6.0
Portunus tenuipes	1	0.7	6.9
Thalamita intermedia	1	0.2	2.2
Thenus maculata	17	252.7	824.6
Thenus orientalis	18	210.5	723.9
Amussiidae	16	22.4	70.2
Gastropoda	1	0.5	4.5
Ostreidae	4	68.4	579.5
Sepioidae	8	57.3	229.0
Teuthoidea	48	1916.2	6318.3
Crinoidea	9	70.3	620.8
Culcita sp.	1	30.9	376.8
Echinoidea	3	4.5	49.2
Gorgonocephalidae	1	0.9	11.3
Holothurioidea	4	167.1	1056.8
Laganidae	1	0.0	0.2
Stelleroidea: Asteroidea	3	59.9	467.0
Stelleroidea: Ophiuroidea	1	0.0	0.2
Ascidiacea	1	0.2	2.2

Table App.2.C.3 Frequency of occurrence of the most common fish species caught in each cross-shelf stratum during the two survey cruises in the Far Northern Section of the Great Barrier Reef. (*n* = the total number of individuals sampled.)

	PCT OCCURRENCE					
			Stratum Mean			
Class and Species	**A**	**B**	**C**	**D**	**E**	**Total No**
Elasmobranchia						
Amphotistius kuhlii	-	-	4	14	26	22
Carcharhinus limbatus	5	13	-	-	-	18
Gymnura australis	2	23	4	-	-	22
Rhizoprionodon acutus	26	18	-	-	-	27
Teleostii						
Alepes sp	29	53	26	-	-	786
Apogon fasciatus	19	5	-	-	-	147
Canthigaster compressa	2	-	22	38	53	1103
Carangoides caeruleopinnatus	29	45	15	5	-	494
Carangoides chrysophrys	7	20	15	5	-	123
Carangoides fulvoguttatus	31	5	15	19	11	102
Carangoides gymnostethus	24	33	37	24	16	173
Carangoides hedlandensis	48	53	19	-	-	761
Carangoides humerosus	38	55	11	-	-	222
Carangoides talamparoides	17	23	7	-	-	255
Caranx bucculentus	21	40	15	-	-	3278
Centriscus scutatus	2	5	37	29	5	212
Choerodon cephalotes	62	58	48	19	16	580
Choerodon sp 2	50	65	74	57	21	775
Decapterus russellii	10	28	22	14	32	554
Diagramma pictum	19	35	30	33	58	293
Dussumieria elopsoides	33	30	4	-	-	1028
Epigonus lenimen	-	-	-	-	5	102
Fistularia petimba	57	88	48	14	5	1162
Gazza minuta	21	33	7	-	-	1854
Gerres filamentosus	10	3	-	-	-	177
Gerres oyena	55	65	11	-	-	1575
Glaucosoma magnificum	31	13	11	-	-	509
Gnathanodon speciosus	24	18	26	5	5	445
Herklotsichthys lippa	29	35	15	10	5	819
Lagocephalus sceleratus	52	48	41	24	5	693
Leiognathus bindus	74	85	26	-	5	35133
Leiognathus leuciscus	50	23	4	-	-	836
Leiognathus smithursti	10	-	-	-	-	146
Leiognathus sp	98	95	48	5	-	123008
Lethrinus genivittatus	93	98	85	90	100	46680
Lethrinus laticaudis	17	13	15	19	5	353
Lutjanus lutjanus	2	-	-	-	-	120
Lutjanus sebae	2	13	11	-	58	83
Lutjanus vittus	26	20	11	10	26	646
Mene maculata	17	20	15	-	-	2343
Nemipterus furcosus	86	93	96	90	47	7193
Nemipterus hexodon	36	43	7	-	-	276

	PCT OCCURRENCE					
			Stratum Mean			
Class and Species	**A**	**B**	**C**	**D**	**E**	**Total No**
Nemipterus peronii	26	48	15	5	-	222
Paramonacanthus japonicus	48	43	22	24	11	351
Parupeneus heptacanthus	-	-	4	14	68	160
Pelates quadrilineatus	10	13	7	-	-	7283
Pellona ditchela	-	10	-	-	-	4865
Pentapodus paradiseus	57	58	85	76	58	7228
Pentaprion longimanus	38	50	11	-	-	2869
Plotosus lineatus	7	15	7	-	-	278
Priacanthus tayenus	50	75	22	5	5	808
Pristotis jerdoni	17	13	30	33	89	3835
Pseudalutarius nasicornis	-	-	-	-	42	117
Pterocaesio digramma	-	-	4	10	32	1131
Rastrelliger kanagurta	38	40	26	5	-	642
Saurida micropectoralis	21	20	7	-	-	154
Saurida undosquamis	83	93	85	71	16	2379
Scolopsis affinis	-	-	4	19	63	286
Scolopsis taeniopterus	52	55	41	-	-	1145
Scomberomorus queenslandicus	79	70	22	5	-	651
Secutor insidiator	10	15	-	-	-	299
Selar boops	55	68	22	-	-	7913
Selar crumenophthalmus	5	5	-	10	11	152
Selaroides leptolepis	98	100	59	52	26	77811
Seriolina nigrofasciata	14	38	4	-	-	120
Siganus canaliculatus	88	98	70	38	21	6558
Sillago maculata	26	5	7	-	-	304
Sphyraena flavicauda	19	23	19	5	5	3206
Sphyraena forsteri	31	45	15	-	-	487
Terapon theraps	2	10	7	-	-	237
Torquigener pallimaculatus	55	80	63	19	-	1570
Upeneus asymmetricus	29	15	15	19	21	1956
Upeneus luzonius	31	18	33	33	42	1174
Upeneus moluccensis	19	3	-	-	-	110
Upeneus sulphureus	14	15	-	-	-	143
Upeneus sundaicus	31	25	4	-	-	898
Upeneus tragula	31	28	11	14	21	683

Table App.2.C.4 The biomass of species of fish caught in each stratum and total number caught during the two survey cruises in the Far Northern Section of the Great Barrier Reef, where at least 100 individuals were caught

	MN WT OVERALL PER STN IN KGS					
			Stratum Mean			
Class and Species	**A**	**B**	**C**	**D**	**E**	**Total no.**
Elasmobranchia						
Amphotistius kuhlii	0.00	0.00	0.04	0.44	1.00	22
Carcharhinus limbatus	0.50	0.56	0.00	0.00	0.00	18
Gymnura australis	0.03	0.50	0.15	0.00	0.00	22
Rhizoprionodon acutus	0.79	0.55	0.00	0.00	0.00	27
Teleostii						
Alepes sp	0.34	1.89	0.92	0.00	0.00	786
Apogon fasciatus	0.04	0.00	0.00	0.00	0.00	147
Canthigaster compressa	0.00	0.00	0.02	0.23	0.07	1103
Carangoides caeruleopinnatus	0.53	0.60	0.12	0.09	0.00	494
Carangoides chrysophrys	0.04	0.22	0.25	0.10	0.00	123
Carangoides fulvoguttatus	0.20	0.01	0.03	0.07	0.05	102
Carangoides gymnostethus	0.11	0.14	0.28	0.08	0.07	173
Carangoides hedlandensis	0.76	1.01	0.29	0.00	0.00	761
Carangoides humerosus	0.32	0.63	0.12	0.00	0.00	222
Carangoides talamparoides	0.16	0.24	0.03	0.00	0.00	255
Caranx bucculentus	2.82	5.81	1.25	0.00	0.00	3278
Centriscus scutatus	0.00	0.00	0.04	0.03	0.00	212
Choerodon cephalotes	0.62	0.48	0.68	0.08	0.08	580
Choerodon sp	0.16	0.26	0.46	0.19	0.04	775
Decapterus russellii	0.07	0.11	0.54	0.17	0.21	554
Diagramma pictum	0.87	0.52	1.21	8.58	13.64	293
Dussumieria elopsoides	0.71	0.50	0.01	0.00	0.00	1028
Epigonus lenimen	0.00	0.00	0.00	0.00	0.20	102
Fistularia petimba	0.16	0.26	0.16	0.04	0.00	1162
Gazza minuta	0.16	1.73	0.01	0.00	0.00	1854
Gerres filamentosus	0.12	0.01	0.00	0.00	0.00	177
Gerres oyena	0.90	0.53	0.29	0.00	0.00	1575
Glaucosoma magnificum	0.23	0.59	0.04	0.00	0.00	509
Gnathanodon speciosus	0.32	2.69	2.00	0.60	0.00	445
Herklotsichthys lippa	0.27	0.26	0.05	0.11	0.00	819
Lagocephalus sceleratus	0.21	0.28	0.10	0.02	0.01	693
Leiognathus bindus	3.71	5.71	0.54	0.00	0.00	35133
Leiognathus leuciscus	0.29	0.06	0.02	0.00	0.00	836
Leiognathus smithursti	0.10	0.00	0.00	0.00	0.00	146
Leiognathus sp	25.89	34.96	6.25	0.00	0.00	123008
Lethrinus genivittatus	8.29	10.77	11.58	24.67	22.99	46680
Lethrinus laticaudis	0.53	0.99	1.16	1.39	0.03	353
Lutjanus lutjanus	0.26	0.00	0.00	0.00	0.00	120
Lutjanus sebae	0.05	0.05	0.09	0.00	6.51	83
Lutjanus vittus	0.97	0.79	0.43	0.06	0.87	646
Mene maculata	1.07	1.04	1.49	0.00	0.00	2343
Nemipterus furcosus	3.88	5.65	8.02	4.90	0.29	7193
Nemipterus hexodon	0.11	0.57	0.02	0.00	0.00	276
Nemipterus peronii	0.06	0.20	0.06	0.00	0.00	222
Paramonacanthus japonicus	0.04	0.06	0.02	0.07	0.00	351

MN WT OVERALL PER STN IN KGS

	Stratum Mean					
Class and Species	**A**	**B**	**C**	**D**	**E**	**Total no.**
Parupeneus heptacanthus	0.00	0.00	0.00	0.25	0.44	160
Pelates quadrilineatus	0.16	4.51	0.08	0.00	0.00	7283
Pellona ditchela	0.00	6.62	0.00	0.00	0.00	4865
Pentapodus paradiseus	0.49	0.63	7.67	9.35	0.56	7228
Pentaprion longimanus	0.34	0.48	0.72	0.00	0.00	2869
Plotosus lineatus	0.09	0.01	0.01	0.00	0.00	278
Priacanthus tayenus	0.59	1.00	0.90	0.03	0.00	808
Pristotis jerdoni	0.05	0.03	0.15	0.68	2.21	3835
Pseudalutarius nasicornis	0.00	0.00	0.00	0.00	0.05	117
Pterocaesio digramma	0.00	0.00	0.29	0.26	0.73	1131
Rastrelliger kanagurta	0.45	0.69	0.63	0.07	0.00	642
Saurida micropectoralis	0.42	0.27	0.11	0.00	0.00	154
Saurida undosquamis	1.61	1.66	1.24	0.67	0.04	2379
Scolopsis affinis	0.00	0.00	0.03	0.28	0.88	286
Scolopsis taeniopterus	0.22	0.79	2.44	0.00	0.00	1145
Scomberomorus queenslandicus	3.10	4.24	1.21	0.10	0.00	651
Secutor insidiator	0.07	0.02	0.00	0.00	0.00	299
Selar boops	2.72	8.94	0.98	0.00	0.00	7913
Selar crumenophthalmus	0.06	0.07	0.00	0.11	0.07	152
Selaroides leptolepis	15.44	41.46	9.72	17.07	0.20	77811
Seriolina nigrofasciata	0.34	0.75	0.05	0.00	0.00	120
Siganus canaliculatus	2.58	3.73	1.86	0.48	0.29	6558
Sillago maculata	0.32	0.02	0.21	0.00	0.00	304
Sphyraena flavicauda	2.77	0.13	4.23	0.02	0.21	3206
Sphyraena forsteri	0.43	0.49	0.19	0.00	0.00	487
Terapon theraps	0.00	0.20	0.37	0.00	0.00	237
Torquigener pallimaculatus	0.28	1.12	0.23	0.03	0.00	1570
Upeneus asymmetricus	0.16	0.25	0.27	0.07	2.38	1956
Upeneus luzonius	0.33	0.04	0.21	1.37	0.43	1174
Upeneus moluccensis	0.04	0.00	0.00	0.00	0.00	110
Upeneus sulphureus	0.03	0.05	0.00	0.00	0.00	143
Upeneus sundaicus	0.56	0.16	0.01	0.00	0.00	898
Upeneus tragula	0.12	0.21	0.02	0.06	0.01	683

Table App.2.C.5 The number of animals of fish species caught in each stratum and total number caught during the two survey cruises in the Far Northern Section of the Great Barrier Reef, where at least 100 individuals were caught.

	MN NO OVERALL PER STN					
			Stratum Mean			
Class and Species	**A**	**B**	**C**	**D**	**E**	**Total no**
Elasmobranchia						
Amphotistius kuhlii	0	0	0	0	1	22
Carcharhinus limbatus	0	0	0	0	0	18
Gymnura australis	0	0	0	0	0	22
Rhizoprionodon acutus	0	0	0	0	0	27
Teleostii						
Alepes sp	2	14	5	0	0	786
Apogon fasciatus	3	0	0	0	0	147
Canthigaster compressa	0	0	3	43	6	1103
Carangoides caeruleopinnatus	6	6	1	0	0	494
Carangoides chrysophrys	0	1	2	0	0	123
Carangoides fulvoguttatus	2	0	0	0	0	102
Carangoides gymnostethus	1	1	2	1	1	173
Carangoides hedlandensis	8	8	4	0	0	761
Carangoides humerosus	2	3	1	0	0	222
Carangoides talamparoides	3	3	0	0	0	255
Caranx bucculentus	18	56	11	0	0	3278
Centriscus scutatus	0	0	6	2	0	212
Choerodon cephalotes	7	4	5	0	0	580
Choerodon sp	4	6	10	4	1	775
Decapterus ressellii	1	2	6	5	7	554
Diagramma pictum	1	1	2	4	4	293
Dussumieria elopsoides	15	10	0	0	0	1028
Epigonus lenimen	0	0	0	0	5	102
Fistularia petimba	8	14	8	2	0	1162
Gazza minuta	7	39	0	0	0	1854
Gerres filamentosus	4	0	0	0	0	177
Gerres oyena	27	9	4	0	0	1575
Glaucosoma magnificum	4	8	1	0	0	509
Gnathanodon speciosus	4	1	9	1	0	445
Herklotsichthys lippa	12	6	1	2	0	819
Lagocephalus sceleratus	6	9	3	0	1	693
Leiognathus bindus	390	449	29	0	0	35133
Leiognathus leuciscus	17	2	1	0	0	836
Leiognathus smithursti	3	0	0	0	0	146
Leiognathus sp	1401	1492	166	0	0	12300 8
Lethrinus genivittatus	204	236	209	577	572	46680
Lethrinus laticaudis	2	4	3	1	0	353
Lutjanus lutjanus	3	0	0	0	0	120
Lutjanus sebae	0	0	0	0	2	83
Lutjanus vittus	8	6	2	0	3	646
Mene maculata	20	18	28	0	0	2343
Nemipterus furcosus	43	48	79	60	4	7193
Nemipterus hexodon	2	5	0	0	0	276
Nemipterus peronii	2	3	1	0	0	222

MN NO OVERALL PER STN

Class and Species			**Stratum Mean**			
	A	**B**	**C**	**D**	**E**	**Total no**
Paramonacanthus japonicus	3	3	1	3	0	351
Parupeneus heptacanthus	0	0	0	2	6	160
Pelates quadrilineatus	9	172	1	0	0	7283
Pellona ditchela	0	122	0	0	0	4865
Pentapodus paradiseus	11	12	109	148	11	7228
Pentaprion longimanus	23	29	27	0	0	2869
Plotosus lineatus	4	1	3	0	0	278
Priacanthus tayenus	5	8	10	0	0	808
Pristotis jerdoni	3	2	8	43	131	3835
Pseudalutarius nasicornis	0	0	0	0	6	117
Pterocaesio digramma	0	0	21	4	24	1131
Rastrelliger kanagurta	5	7	5	0	0	642
Saurida micropectoralis	2	1	0	0	0	154
Saurida undosquamis	24	26	9	4	0	2379
Scolopsis affinis	0	0	0	3	11	286
Scolopsis taeniopterus	4	9	24	0	0	1145
Scomberomorus queenslandicus	4	9	5	0	0	651
Secutor insidiator	6	1	0	0	0	299
Selar boops	42	147	10	0	0	7913
Selar crumenophthalmus	1	1	0	2	3	152
Selaroides leptolepis	466	1077	165	503	7	77811
Seriolina nigrofasciata	1	2	0	0	0	120
Siganus canaliculatus	56	77	33	8	4	6558
Sillago maculata	5	0	2	0	0	304
Sphyraena flavicauda	33	1	63	0	2	3206
Sphyraena forsteri	5	6	2	0	0	487
Terapon theraps	0	3	5	0	0	237
Torquigener pallimaculatus	7	29	4	1	0	1570
Upeneus asymmetricus	5	6	7	2	69	1956
Upeneus luzonius	6	1	4	28	10	1174
Upeneus moluccensis	3	0	0	0	0	110
Upeneus sulphureus	2	2	0	0	0	143
Upeneus sundaicus	18	3	0	0	0	898
Upeneus tragula	7	8	0	2	0	683

APPENDIX.2.D

Table App.2.D.1 Listing of the percentage of occurrence, catchrate and standard deviation of benthic material collected in the Church Dredge from the Far Northern Section of the Great Barrier Reef.

(n = 157stations)

Species	%	Catch rate (g h^{-1})	s.d.
Sea grass			
Halophila ovalis	1	2.4	30.3
Halophila spinulosa	2	11.4	97.5
Sponges			
Cinachyra australiensis	1	2.6	27.5
Clathrya vulpina	4	23	139.8
Club sponge sp.1	13	4.8	22.9
Cymbacella sp.	1	7	87.9
Hippospongia elastica	3	37.5	254.9
Ianthella sp.	8	214.5	1313.8
Mushroom Sponge sp.	1	71.2	636.7
Phakellia carteri	1	3.3	41.2
Porifera sp.A	2	5.7	42.1
Porifera sp.GBR2	1	1.2	15.3
Porifera sp.1	5	67.4	527.7
Porifera sp.2	1	0.2	3.1
Porifera sp.3	6	108.5	833.9
Porifera sp.4	1	0.7	9
Porifera sp.5	1	6.5	81.7
Porifera sp.6	1	2.5	29.7
Porifera sp.7	1	20.3	243
Porifera sp.8	7	36.3	250.4
Porifera sp.9	4	3	21.9
Porifera sp.10	37	1480.7	7790
Porifera sp.11	3	60.7	670.3
Porifera sp.12	1	0.6	6.9
Porifera sp.12/39	1	41.7	522.3
Porifera sp.14	9	57.2	492.3
Porifera sp.15	1	1.5	18.3
Porifera sp.17	6	40.2	409.4
Porifera sp.18	13	5.1	26.8
Porifera sp.20	1	22.5	281.6
Porifera sp.22	2	1.4	14.4
Porifera sp.23	3	5.8	47.5
Porifera sp.25	3	49.8	366.9
Porifera sp.26	1	5	44.3
Porifera sp.27	2	0.9	6.3
Porifera sp.28	3	9	66.6
Porifera sp.30	2	71.6	523.3
Porifera sp.34/90A	1	3	37.3
Porifera sp.34/90B	1	0.7	8.2
Porifera sp.34/90C	1	10.8	135.3
Porifera sp.35	4	85.6	903.4
Porifera sp.36	25	1244	3429.3
Porifera sp.38	3	63.7	412.8
Porifera sp.39	1	2.1	23.5
Porifera sp.40	4	3.6	25.1
Porifera sp.42	16	378.3	2356.4

Species	**%**	**Catch rate (g h^{-1})**	**s.d.**
Porifera sp.44	4	20.7	137.4
Porifera sp.45	1	10.5	131.8
Porifera sp.46	9	6.6	33
Porifera sp.47	7	6.6	31
Porifera sp.49	15	289.8	2795.2
Porifera sp.50	4	34	375.6
Porifera sp.51	1	1.6	14.2
Porifera sp.55	2	16.7	180.3
Porifera sp.56	1	1.5	19.3
Porifera sp.57	3	38.3	430.3
Porifera sp.58	1	0.3	3.1
Porifera sp.58/42	3	2.1	14.3
Porifera sp.59	6	20	108.4
Porifera sp.60	1	0.3	3.5
Porifera sp.61	2	204	2494.2
Porifera sp.63	1	0.7	8.6
Porifera sp.67	1	28.8	360.9
Porifera sp.73	3	18.4	126.3
Porifera sp.74	4	58.2	362
Porifera sp.75	1	0.2	3
Porifera sp.75/62	13	707.6	7503.6
Porifera sp.76	3	8.1	53.1
Porifera sp.77	1	1	12.2
Porifera sp.81	1	0.7	9
Porifera sp.82	2	2	16.4
Porifera sp.83	1	3	27.1
Porifera sp.83/12A	1	3.7	46.4
Porifera sp.86	1	2.8	31
Porifera sp.94	3	176	1919.7
Porifera sp.97	1	4	50.2
Porifera sp.99	2	2.9	22
Porifera sp.104	1	499.3	6255.6
Porifera sp.120	4	399.4	3829.5
Porifera sp.121	8	73.4	435.9
Porifera sp.122	6	96.9	695.9
Porifera sp.123	8	326.9	2446
Porifera sp.126	1	26.1	327.2
Porifera sp.141	1	58.7	735.6
Porifera	15	9876.3	67494.1
Raspalia sp.	1	1	13
Cnidaria			
Acropora sp.2	5	686.9	4350.6
Acropora sp.3	1	192.5	2044.3
Acropora sp.4	1	3.5	41.8
Acropora sp.5	1	112.5	1100.0
Acropora sp.6	2	10.3	86.4
Acropora sp.7	1	15.5	193.8
Acropora sp.8	1	28.1	306.4
Alcyonacians (mixed spp.)	5	31.0	209.7
Dendronephthya sp	40	140.5	609.7
Nepthigorgia sp	26	58.4	328.9
Solenocaulon sp	27	47.2	116.0
Alcyonarian sp.12	1	2.3	29.1
Alcyonarian sp.13	1	0.1	1.4
Alcyonarian sp.14	2	26.8	312.0
Subergorgia sp	21	99.4	280.8
Alcyonarian sp.16	3	95.5	765.6
Alcyonarian sp.17	1	4.2	44.7
Dendronephthya sp.18	8	80.1	432.3
Alcyonarian sp.19	9	102.2	545.3
Umbellulifera sp	13	115.7	545.8
Alcyonarian sp.20	3	6.9	51.9
Dendronephthya sp.21	6	95.4	678.0

Species	%	Catch rate (g h^{-1})	s.d.
Studeroites sp	27	118.0	957.2
Morchellana sp	25	44.9	189.3
Alcyonarian sp.5	2	2.6	25.5
Alcyonarian sp.6	1	0.5	5.9
Umbellulifera sp.7	1	0.1	1.4
Alcyonarian sp.8	22	123.0	407.9
Alcyonarian sp.9	4	5.1	33.2
Anemone sp.1	1	0.3	4.3
Anemone sp.2	3	0.6	5.0
Anemone sp.3	4	1.1	7.4
Anemone sp.4	1	0.1	0.9
Anemone sp.5	1	0.7	8.3
Favid sp.1	1	11.1	113.7
Favid sp.2	3	369.9	3535.1
Flabellum sp.	40	66.8	131.1
Fungia sp.1	40	1239.8	5635.2
Fungia sp.2	4	16.9	116.7
Fungia sp.3	10	232.1	1448.0
Fungia sp.4	11	286.6	1587.6
Fungia sp.5	5	3.8	19.0
Gorgonacea (mixed spp.)	1	20.3	184.5
Gorgonian sp.1	3	1.8	11.8
Gorgonian sp.10	3	176.3	1583.7
Gorgonian sp.11	2	16.4	157.9
Gorgonian sp.12	1	4.3	53.3
Gorgonian sp.13	3	527.8	4939.6
Gorgonian sp.14	2	9.4	83.3
Gorgonian sp.15	2	14.6	124.3
Gorgonian sp.16	1	3.6	42.1
Gorgonian sp.17	2	7.6	77.1
Gorgonian sp.18	1	25.7	321.8
Gorgonian sp.2	5	11.8	96.2
Gorgonian sp.3	13	7.8	43.2
Gorgonian sp.4	1	0.2	2.1
Gorgonian sp.8	1	1.8	22.7
Hydroid sp.19	1	4.0	35.1
Hydroid sp.21	1	0.2	1.5
Hydroid sp.22	1	0.3	3.7
Hydroid sp.23	1	0.8	9.6
Hydroid sp.3	5	4.2	33.0
Hydroid sp.4	2	0.4	3.0
Hydroid sp.5	14	2.4	8.5
Hydroid sp.6	4	6.9	65.0
Hydroid sp.7	1	0.2	2.0
Hydroid sp.8	1	0.3	2.4
Hydroid sp.9	33	319.7	1219.2
Hydroid (mixed spp.)	1	15.8	198.1
Lobophyta sp.	1	141.4	1616.2
Palythoa sp.	1	12.4	155.3
Porites sp.1	1	52.1	607.6
Pennatulacea sp.1	6	9.7	77.7
Pennatulacea sp.2	1	1.8	22.6
Pennatulacea sp.4	5	0.5	3.1
Pennatulacea sp.5	1	0.7	7.3
Pennatulacea sp.6	3	1.1	8.0
Pennatulacea sp.7	4	6.2	45.1
Madreporian solitary coral sp.3	1	0.1	0.7
Madreporian solitary coral sp.4	1	0.1	1.2
Madreporian solitary coral sp.5	1	0.1	1.4
Sarcophyta sp.	4	257.5	2731.7
Scleratinia (mixed spp.)	1	2303.1	27787.6
Scleratinid sp.	2	27.6	294.2
Sphaenopus sp.1	77	1548.5	3804.9

Species	%	Catch rate (g h^{-1})	s.d.
Tubastrea sp.	1	1.0	12.4
Tubipora musica	1	3.6	44.7
Zooanthid sp.1	1	0.0	0.5
Polychaetes			
Polychaete (mixed spp.)	1	92.6	821.8
Crustaceans			
Actaea savignii	1	0.1	0.8
Actaeodes mutatus	1	0.0	0.5
Actumnus dorsipes	1	0.2	1.7
Actumnus setifer	1	0.4	4.6
Alpheid sp.1	1	0.1	0.9
Alpheid sp.10	1	0.2	2.4
Alpheid sp.7	1	0.0	0.3
Alpheid sp.9	1	0.1	1.5
Alpheidae (mixed spp.)	6	1.1	5.6
Arcania novemspinosa	3	0.6	4.1
Arcania sp.	1	0.8	8.4
Balanus sp.	3	3.4	30.1
Banareia sp.	1	0.1	1.2
Bathypilumnus nigrispinifer	1	2.2	25.3
Bathypilumnus pugilator	6	0.8	3.5
Calappa gallus	4	15.1	135.0
Calappa philargius	1	5.3	66.0
Calappa sp.1	1	0.4	4.5
Calappa sp.2	7	1.9	9.2
Calappa sp.3	1	0.4	4.7
Calappa terraereginae	31	30.0	75.4
Camposcia retusa	1	0.0	0.6
Carid sp.10	1	0.1	0.8
Carid sp.4	2	0.1	0.8
Carid sp.9	6	0.4	2.1
Caridea (mixed spp.)	5	1.2	7.0
Carinosquilla ulticarinata	4	0.7	3.8
Ceratoplax sp.1	4	2.6	27.2
Ceratoplax sp.3	3	0.1	0.6
Ceratoplax sp.4	1	0.1	0.5
Ceratoplax sp.5	1	0.0	0.0
Ceratoplax sp.6	1	0.0	0.2
Charybdis jaubertensis	8	3.9	22.3
Charybdis truncata	3	2.9	28.7
Chlorinoides aculeatus	1	0.0	0.6
Chlorodiella sp.	1	0.1	1.4
Clibanarius sp.	4	0.2	1.1
Colloides sp.	1	0.4	3.1
Coronidopsis serenei	1	0.7	8.9
Cryptocoeloma haswelli	1	0.1	1.7
Cryptopodia sp.3	19	4.1	11.3
Cryptopodia sp.4	3	5.1	45.4
Cryptopodia spatulifrons	1	0.1	1.8
Daldorfia investigatoris	1	0.0	0.4
Dardanus diery	3	0.9	5.9
Dardanus asperus	1	0.2	2.1
Dardanus hessii	2	0.6	5.3
Dardanus imbricata	26	9.8	25.1
Dardanus lagopodes	1	0.0	0.3
Dardanus pedunculatus	3	3.0	28.6
Dardanus sp.1	1	0.1	0.7
Dardanus sp.2	1	1.0	11.7
Diogenes sp.1	1	0.1	1.1
Diogenes sp.2	1	0.0	0.3
Diogenes sp.3	13	0.9	6.1

Species	**%**	**Catch rate** $(g\ h^{-1})$	**s.d.**
Dorippe frascone	21	15.9	42.5
Dromid sp.1/93	1	0.2	1.8
Dromid sp.73/98	1	0.3	2.6
Dromid sp.G1	3	1.0	7.3
Dromid sp.G2	1	0.2	2.8
Dromidia sp.	2	0.7	5.8
Dromidiopsis edwardsi	1	2.0	25.5
Ebalia lambriformis	4	0.5	4.3
Eucrate sp.7	1	0.0	0.5
Galatheid sp.1	2	0.1	1.5
Galatheid sp.3	1	0.0	0.3
Gonodactylidae	1	0.6	7.4
Gonodactylus graphurus	6	2.4	12.6
Harrovia sp.3	1	0.0	0.2
Huenia heraldica	2	0.9	7.5
Hyastenus cambelli	6	1.2	5.0
Hyastenus sp.1	8	4.0	23.8
Hyastenus sp.2	2	2.5	29.6
Hyastenus sp.3	3	0.7	5.2
Hyastenus sp.4	14	100.4	413.8
Ixa inermis	9	2.0	7.0
Ixoides cornutus	1	0.2	2.3
Jonas luteanus	1	0.2	2.2
Lasiodroma coppingeria	1	0.2	2.0
Lepas sp.2	2	0.3	3.8
Leucosia anatum	3	0.2	1.8
Leucosia magna	5	2.8	14.3
Leucosia marganitata	1	0.0	0.1
Leucosia ocellata	22	11.2	27.4
Leucosia sp.2	1	0.2	2.5
Leucosia whitei	4	0.8	4.7
Lisocarcinus polyboides	1	0.2	1.8
Lupocyclus rotundatus	2	0.7	5.8
Lupocyclus tugelae	1	0.1	1.1
Majidae sp.1	4	0.4	2.2
Majidae sp.2	3	0.5	4.0
Matuta inermis	6	126.9	993.7
Medaeops granulosus	1	0.0	0.1
Metapenaeopsis crassissima	1	0.1	0.6
Metapenaeopsis palmensis	26	7.3	19.3
Metapenaeopsis sp.	1	0.3	4.1
Metapenaeus endeavouri	17	21.9	94.5
Metapenaeus ensis	1	0.1	1.6
Metapenaeus moyebi	1	0.4	5.4
Micippa excavata	4	3.8	29.2
Micippa sp.	4	2.0	11.2
Myra biconica	1	0.4	4.3
Myra mammilaris	1	0.6	7.6
Myrodes eudactylus	1	0.4	3.5
Naxoides tenuirostris	2	0.1	0.9
Oratosquilla perpensa	3	2.3	18.6
Oratosquilla woodmasoni	1	1.1	13.3
Oreophorus moram	1	0.0	0.2
Oreophorus sp.1	1	0.0	0.1
Pagurid sp.2	7	3.4	20.3
Pagurus sp.1	1	0.0	0.5
Palicoides longimanus	1	2.8	33.8
Palicus sp.1	1	0.6	5.9
Parthenope harpax	16	7.3	33.6
Parthenope hoplonotus	16	4.6	12.9
Parthenope longimanus	25	12.5	35.5
Parthenope longispinus	9	3.7	18.6
Penaeus esculentus	21	96.5	299.5

Species	**%**	**Catch rate ($g\ h^{-1}$)**	**s.d.**
Penaeus latisulcatus	7	16.2	70.1
Penaeus longistylus	11	18.0	63.4
Penaeus semisulcatus	2	27.5	310.0
Phalangipes australiensis	16	2.3	8.2
Phalangipes longipes	9	1.2	10.3
Pilumnus pulcher	1	0.1	1.1
Pilumnus semilanatus	7	1.8	8.3
Pilumnus sp.1	11	1.7	8.9
Pilumnus sp.4	1	0.0	0.2
Pilumnus sp.X	1	0.1	0.6
Planopilumnus labyrinthicus	1	0.2	3.1
Platypodia sp.	1	2.7	33.3
Polyonyx sp.	1	0.0	0.3
Porcellanidae sp.6	2	0.1	1.1
Porcellanidae sp.9	1	0.0	0.1
Portunus argentatus	1	0.2	2.1
Portunus gracilimanus	26	19.8	51.2
Portunus granulatus	3	0.4	2.2
Portunus pelagicus	7	28.6	143.5
Portunus rubromarginatus	51	163.9	266.0
Portunus rugosus	2	0.9	9.4
Portunus sp.1	1	0.0	0.4
Portunus tenuipes	43	170.3	482.5
Pseudomicippe sp.	1	0.4	3.4
Pseudosquilla sp.	1	0.3	3.2
Scyllarus demani	13	10.5	40.2
Scyllarus sp.1	1	0.2	1.9
Sicyonia sp.	1	0.5	5.7
Solenocera pectinata	1	0.1	0.5
Spiropagurus sp.1	1	0.1	1.0
Spiropagurus sp.3	9	0.3	1.5
Stenopus hispidus	1	0.1	0.8
Stomatopoda (mixed spp.)	1	0.2	3.1
Thalamita bouveri	2	4.9	58.2
Thalamita intermedia	4	0.7	4.6
Thalamita malaccensis	1	0.1	0.7
Thalamita sexlobata	2	0.2	2.0
Thalamita sima	8	2.5	12.1
Thalassina sp.1	1	0.1	0.6
Thenus orientalis	14	118.7	550.9
Thenus sp.B	5	50.3	234.0
Trachypenaeus anchoralis	2	0.2	1.4
Trachypenaeus fulvus	1	0.1	1.1
Trachypenaeus granulosus	15	2.9	10.2
Trapezia cymodoce	1	0.5	5.9
Trizopagurus strigatus	1	0.0	0.3
Xanthid sp.A	6	0.2	1.1
Zebra sp.1	1	0.1	0.9
Mollusca			
Acrosterigma flava	1	3.8	46.7
Amoria damoni	3	1.0	7.1
Amoria turneri	3	1.0	7.2
Amusium pleuronectes	44	196.2	688.5
Amusiidae	4	19.8	150.8
Anadara granosa	3	9.0	107.2
Ancilla cingulata	2	2.1	19.0
Annachlamys flabellata	14	11.7	45.0
Antigona chemnitzii	1	0.3	3.9
Antigonia lamellaris	30	27.7	146.2
Arca navicularis	11	2.0	7.8
Architectonica perspectiva	1	0.1	0.9
Atys naucum	3	0.4	2.6

Species	**%**	**Catch rate (g h^{-1})**	**s.d.**
Azorinus minitus	1	0.1	1.5
Barbatia foliata	8	4.6	22.0
Bassina calophylla	33	85.6	331.4
Bursa margaritula	3	0.8	5.8
Bursa oyanai	5	41.6	299.4
Bursa rana	14	6.7	20.1
Calliostoma monile	1	0.1	1.1
Calliostoma speciosa	1	0.3	4.0
Callista semisulcata	1	0.2	2.5
Calvus formidabilis	1	0.2	2.8
Cancilla interlirata	1	0.1	0.7
Cardita crassicosta	6	7.6	59.3
Cardium frazeri	2	0.3	2.4
Ceratosoma cornigerum	4	10.2	107.8
Cerithium pseudovertagus	1	0.3	3.4
Chama asperella	1	1.0	13.1
Chama fimbriata	1	0.1	1.3
Chama pacifica	3	139.7	1649.8
Chama pulchella	3	2.4	17.7
Chama sp.	3	16.2	145.4
Chicoreus akritos	2	1.6	13.5
Chicoreus banksii	8	33.9	274.3
Chicoreus cervicornis	41	44.9	126.0
Chicoreus cornucervis	1	0.2	3.1
Chlamys gloryiosus	4	2.5	17.3
Chromodoris lineolata	1	0.9	11.4
Circe personata	1	0.5	5.9
Circe scripta	8	5.6	27.8
Circe sulcata	3	0.9	7.0
Cirith sp.	1	0.7	8.6
Clavis sp.	1	0.3	3.0
Conus aculeformis	1	0.1	1.0
Conus adami	1	1.7	21.2
Conus ammiralis	1	7.5	65.8
Conus lynceus	2	1.8	18.1
Conus suturatus	3	1.0	7.4
Conus tessulatus	4	2.8	17.2
Coralliophila pyriformis	1	0.9	11.9
Corbula macgillivrayi	3	0.5	3.2
Corbula scaphoides	4	1.4	8.8
Crenatula modiolaris	1	0.0	0.2
Crenatula viridis	1	0.1	1.3
Cronia aurantiaca	1	1.2	14.9
Cronia contracta	8	2.1	15.6
Crypopecten nux	1	0.1	0.5
Ctenocardia virgo	8	4.2	35.4
Cucullaea labiata	16	31.2	176.8
Cultellus cultellus	5	5.2	49.5
Cymatium caudatum	3	1.5	13.0
Cymatium pfeifferianum	6	1.8	10.2
Cymatium pileare	1	1.6	19.7
Cymbiola cymbiola	1	1.1	13.7
Cymbiola sophia	29	35.7	97.8
Cypraea caurica	1	0.8	10.4
Cypraea subviridis	4	3.9	26.4
Cypraea walkeri	3	3.1	28.8
Decatopecten strangei	4	2.4	15.6
Dendostraea folium	7	24.3	136.1
Dentalium javanum	3	0.1	0.8
Distorsio reticularis	12	7.4	27.7
Dosinia altenai	28	50.6	162.9
Dosinia juvinilis	9	4.0	15.8
Dosinia mira	1	0.7	8.3

Species	%	Catch rate (g h^{-1})	s.d.
Echelus atratus	9	4.6	36.2
Ennucula superba	2	0.2	1.8
Ethalia guamensis	1	0.0	0.6
Eulimid sp.	1	0.0	0.1
Fragum retusum	13	11.9	80.3
Fulvia aperta	1	0.1	1.4
Fulvia australe	1	0.1	1.4
Fulvia sp.nov.2	1	0.1	0.7
Fusinus colus	5	2.7	15.8
Gastropoda (mixed spp.)	3	255.4	3035.7
Gemmula hastula	3	0.3	2.0
Gemmula murrayi	1	0.1	0.9
Gyrineum gyrineum	2	0.6	5.1
Gyrineum pusillum	1	0.2	1.6
Haustellum multiplicatum	1	0.3	3.4
Hexabranchus sanguineus	1	2.2	27.3
Hyatina hyotis	16	250.6	1949.6
Inquisitor sterrhus	1	0.1	1.6
Isognomon sp.1	1	0.4	5.3
Lataxiena fimbriata	1	0.1	0.6
Laternula cumingi	1	0.1	1.2
Latirus paetelianus	4	0.9	5.3
Laxatenia fimbriata	1	0.1	0.9
Levicardium attenuata	3	1.3	14.7
Limaria basilanica	1	1.1	13.5
Limopsis sp.1	3	0.4	3.3
Lioconcha ornata	1	0.1	0.7
Lioconcha polita	3	0.7	4.7
Lirularia sp.	1	0.0	0.6
Lopha sp.	3	8.0	55.6
Lophiotoma indica	11	9.4	50.0
Macoma candida	1	0.3	3.2
Mactra artensis	3	1.5	17.3
Malleus albus	18	48.5	158.5
Malleus malleus	3	8.1	69.9
Margovula pyriformis	1	0.1	0.8
Melaxinia vitrea	42	92.6	283.7
Mimachlamys scabricostata	3	0.9	7.1
Minnivola sp.nov.2	1	0.1	1.0
Mipus gyratus	1	1.6	19.5
Mitra fulgurita	1	0.2	1.9
Modiolis glaberrina	1	0.0	0.6
Modiolis hanleyi	1	0.1	1.3
Modiolis philippinarum	1	4.7	56.9
Modiolus elongata	3	0.8	6.1
Modiolus metcalfei	4	2.9	22.2
Modiolus ostentatus	11	4.2	19.3
Modiolus proclivis	5	0.8	3.9
Modiolus vagina	5	3.4	26.6
Mollusca (mixed spp.)	1	3.5	43.5
Murex acanthostephes	4	2.6	16.0
Murex macgillivrayi	15	13.5	70.9
Murex pecten	6	11.2	58.2
Nassarius acuminata	1	0.0	0.5
Nassarius compyus	1	0.1	1.6
Nassarius conoidalis	2	0.2	1.4
Nassarius glans	1	0.0	0.5
Natica alapapilionis	1	0.0	0.6
Natica arachnoidea	1	0.3	4.2
Natica solida	1	0.7	8.9
Neocancilla clathrus	1	0.1	1.7
Neotrigonia uniophora	6	3.3	18.2
Nucula cumingii	1	0.0	0.1

Species	**%**	**Catch rate ($g\ h^{-1}$)**	**s.d.**
Nudibranch sp.B	1	0.1	1.4
Nudibranch sp.G	1	0.1	0.8
Nudibranch sp.M	1	0.5	6.6
Nudibranch sp.N	3	1.8	11.6
Nudibranch sp.Q	1	3.6	43.4
Nudibranch sp.U	1	1.1	10.0
Nudibranch sp.V	1	0.2	2.2
Octopoda sp.	2	4.2	38.5
Oliva miniacea	1	2.6	33.2
Paphia semirugata	18	8.8	25.0
Paphia subrugata	1	0.4	4.8
Patelliel sp.1	1	0.0	0.1
Phalium bandatum	1	1.8	22.2
Phalium bisulcatum	3	0.5	3.4
Phalium glabratum	3	0.6	4.0
Phenacovolva rosea	1	0.1	1.0
Philine sp.A	3	1.3	9.3
Philine sp.B	1	0.8	8.7
Phos roseatus	1	0.2	3.0
Phos senticosus	1	0.3	3.1
Pinctada fucata	7	2463.0	14117.5
Pinctada maculata	1	295.7	3705.1
Pinctada sugillata	4	7.3	58.6
Pinna muricata	6	3.0	23.1
Pitar spoori	1	1.2	12.7
Placamen tiara	3	0.2	1.3
Placuna lincolni	10	22.7	87.4
Placuna lubata	1	1.7	15.1
Plicatula essingtonensis	16	10.8	55.9
Polinices albumen	1	0.5	5.7
Polinices draparnaudi	1	0.2	2.2
Polinices peselephanti	1	0.2	3.1
Pteria lata	2	4.8	40.5
Pteria sp.2	3	0.3	2.1
Pteria zebra	9	4.9	25.8
Pterynotus alatus	1	0.4	3.9
Pyramidella ascus	3	0.5	3.4
Rapana sp.	1	0.4	4.6
Rhinoclavis asperus	1	1.9	23.5
Rhinoclavis fasciata	3	7.2	52.8
Rhinoclavis kochi	4	1.4	8.3
Scapharea vellicata	5	2.9	15.7
Semele amabilis	4	2.3	16.4
Semele exarata	1	0.5	4.9
Sepioidea sp.5	4	9.6	70.0
Sepioidea sp.1	15	120.5	557.5
Sepioidea sp.2	14	38.5	115.9
Sepioidea sp.3	7	12.9	60.5
Sepioidea sp.4	2	2.5	19.2
Sinum sp.nov.	1	0.6	7.4
Siratus laciniatus	1	1.4	15.9
Solen albomacalata	4	1.4	8.8
Spondylus barbatus	3	1.4	13.8
Spondylus sp.	1	15.6	195.2
Spondylus victoriae	1	6.3	79.5
Spondylus wrightianus	20	47.3	144.3
Strombus campbelli	6	10.6	71.8
Strombus diliatus	12	59.9	614.8
Strombus erythrinus	1	22.9	286.1
Strombus labiatus	4	1.3	8.7
Strombus sp.	1	1.0	13.1
Strombus variabilis	1	5.7	71.8
Strombus vittatus	35	66.3	202.6

Species	**%**	**Catch rate (g h^{-1})**	**s.d.**
Syrinx aruanus	4	9.7	60.5
Talibrica donharrisi	1	0.1	0.7
Tellina arafurensis	1	0.0	0.2
Tellina inflata	1	0.7	6.3
Tellina pulcherrima	5	1.1	5.2
Terebellum terebellum	3	2.9	21.8
Terebra triseriata	1	0.3	3.3
Trisidos semitorta	14	11.9	47.4
Tudivasum armigerum	4	12.8	66.3
Tudivasum spinosum	1	178.3	2234.6
Turbo sp.1	1	0.6	7.7
Turbo sp.2	1	0.1	0.7
Turris undosa	1	0.5	6.1
Vepricardium multispinosum	19	12.0	45.9
Vexillum taeniatum	3	2.5	17.7
Vexitoma rega	1	0.2	3.1
Vitularia miliaris	1	1.0	12.6
Volutid sp.	3	170.6	1514.8
Volva volva	11	3.8	21.9
Xenophora cera	4	10.4	72.9
Xenophora indica	3	1.9	14.7
Xenophora solarioides	22	8.4	24.9
Bryozoans			
Adeonellopsis sp.	6	13.2	93.3
Amathia sp.	8	3.2	19.3
Bryozoan sp.1	4	32.1	323.3
Bryozoan sp.11	5	61.9	590.5
Bryozoan sp.13	1	0.2	3.1
Bryozoan sp.17	3	24.4	241.6
Bryozoan sp.18	9	239.1	1903.7
Bryozoan sp.2	7	222.6	2551.4
Bryozoan sp.23	21	141.9	691.4
Bryozoan sp.24	2	7.2	74.8
Bryozoan sp.25	1	4.2	52.7
Bryozoan sp.27	1	1.5	19.0
Bryozoan sp.28	1	7.1	83.9
Bryozoan sp.29	1	0.7	9.3
Bryozoan sp.3	13	10.1	44.3
Bryozoan sp.33	1	0.5	6.5
Bryozoan sp.34	1	14.0	171.2
Bryozoan sp.6	20	73.6	603.2
Bryozoan sp.8	11	96.8	671.1
Bryozoan sp.9	21	35.7	117.8
Phidoloporidae sp.	1	3.4	43.0
Retiflustia cornea	17	9.4	30.1
Scrupocellaria sp.	13	28.4	148.9
Triphyllozoon sp.	20	33.0	143.3
Echinoderms			
Acaudina sp.1	1	2.2	23.1
Acaudina sp.2	1	0.8	10.6
Acaudina sp.3	6	33.0	194.1
Acaudina sp.4	1	6.8	85.2
Asteroid (mixed spp.)	12	1088.1	4668.5
Asteroid sp.11	7	16.5	104.2
Asteroid sp.12	4	7.7	52.3
Asteroid sp.14	4	8.4	49.5
Asteroid sp.17	3	6.7	45.1
Asteroid sp.18	3	31.7	295.5
Asteroid sp.21	1	0.1	0.9
Asteroid sp.22	3	96.6	758.1
Asteroid sp.6	1	2.3	25.3

Species	%	Catch rate (g h^{-1})	s.d.
Astropecten granulatus	50	94.8	312.4
Astropecten polyacanthus	1	0.1	0.8
Astropecten sp.1	3	0.6	4.4
Astropecten sp.4	38	41.3	98.7
Bohadschia argus	1	7.0	87.2
Bohadschia marmorata	1	252.6	2392.5
Brissopsis sp.2	36	59.3	185.8
Brissopsis sp.	11	8.6	47.4
Chaetodiadema ranulatum	4	15.5	84.2
Clypeaster sp.2	6	33.4	177.8
Crinoid sp.1	1	0.4	4.5
Crinoid sp.10	1	0.9	9.8
Crinoid sp.12	8	26.3	133.8
Crinoid sp.13	4	3.4	29.5
Crinoid sp.14	4	4.2	23.3
Crinoid sp.15	40	760.9	1858.7
Crinoid sp.16	9	91.2	492.4
Crinoid sp.17	48	1523.9	5503.0
Crinoid sp.19	28	131.5	364.7
Crinoid sp.2	1	0.4	5.0
Crinoid sp.21	13	109.8	364.7
Crinoid sp.22	18	283.1	1135.5
Crinoid sp.25	1	1.4	13.6
Crinoid sp.26	14	449.3	3588.3
Crinoid sp.27	25	784.1	3735.9
Crinoid sp.28	4	14.0	86.7
Crinoid sp.29	1	0.5	6.3
Crinoid sp.3	3	4.5	38.4
Crinoid sp.4	1	1.2	15.1
Crinoid sp.5	39	1170.0	5779.4
Crinoid sp.7	3	9.5	103.4
Crinoid sp.8	1	0.1	0.9
Crinoid sp.9	3	1.9	15.0
Crinoidea	8	1728.1	8973.7
Culcita sp.	1	50.9	637.7
Echinoid sp.1	1	1.0	12.8
Echinoid sp.10	1	5.3	47.6
Echinoid sp.12	2	16.7	146.8
Echinoid sp.2	4	3.3	32.6
Echinoid sp.3	8	21.5	99.4
Echinoid sp.4	1	0.2	2.2
Echinoid sp.6	11	14.2	65.5
Echinoid sp.7	6	4.8	33.5
Echinoid sp.8	1	1.0	8.9
Echinoid sp.9	3	52.3	588.7
Echinoidea	6	2003.7	16907.0
Euretaster insignis	13	24.4	99.1
Gorgonocephalid sp.1	18	105.5	813.4
Gorgonocephalid sp.2	3	7.2	46.8
Holothuria edulus	1	19.9	249.2
Holothuria ocellata	30	88.7	264.8
Holothuria pervicax	6	26.4	180.9
Holothurian sp.25	1	0.3	2.9
Holothurian sp.26	6	37.0	160.2
Holothurian sp.27	1	6.5	82.0
Holothurian sp.3	7	37.7	293.6
Holothurian sp.30	1	0.2	1.9
Holothurian sp.37	4	168.0	1100.3
Holothurian sp.38	14	2260.4	12105.5
Holothurian sp.39	6	372.9	1891.7
Holothurian sp.40	1	112.1	1404.6
Holothurian sp.G1	1	4.6	58.1
Holothurioidea (mixed spp.)	3	18.5	112.7

Species	**%**	**Catch rate (g h^{-1})**	**s.d.**
Iconaster longimanus	21	38.6	120.5
Laganum sp.1	3	3.3	37.6
Laganum sp.2	28	12.0	34.0
Laganum sp.3	54	539.3	1500.8
Laganum sp.4	4	5.9	55.0
Laganum sp.12	1	1.3	15.7
Laganum sp.4	1	0.2	3.0
Laganum sp.5	2	3.9	32.7
Laganum sp.8	35	335.1	1016.4
Leptopentacta grisea	1	0.4	5.6
Linckia guildingi	1	8.4	105.6
Linckia laevigata	1	4.4	54.8
Luidia hardwicki	4	4.5	31.4
Luidia maculata	8	63.3	336.3
Maretia ovata	22	4915.1	42081.2
Metrodira subulata	42	31.3	71.1
Ophiuroid (mixed spp.)	3	1.9	12.8
Ophiuroid sp.1	33	24.1	85.2
Ophiuroid sp.10	2	0.5	3.9
Ophiuroid sp.15	3	1.1	7.7
Ophiuroid sp.2	1	0.0	0.4
Ophiuroid sp.20	1	0.6	7.7
Ophiuroid sp.21	1	1.5	19.3
Ophiuroid sp.22	2	0.7	6.9
Ophiuroid sp.25	2	0.1	1.1
Ophiuroid sp.28	3	0.8	5.2
Ophiuroid sp.3	3	0.4	3.9
Ophiuroid sp.30	3	0.7	4.1
Ophiuroid sp.31	3	1.0	9.9
Ophiuroid sp.34	19	57.2	223.1
Ophiuroid sp.35	1	3.3	41.1
Ophiuroid sp.38	1	0.3	3.4
Ophiuroid sp.5	9	4.6	17.9
Ophiuroid sp.6	5	1.2	6.2
Ophiuroid sp.9	1	0.1	0.6
Pentaceraster sp.	8	668.1	3430.1
Pentaceraster sp.2	4	313.8	1913.4
Pentacta anceps	27	45.9	116.8
Prionocidaris sp.1	4	4.4	27.1
Prionocidaris sp.2	18	37.1	145.8
Pseudocolochirus axiologus	2	16.6	195.2
Rhinobrissus sp.	1	4.8	47.3
Stellaster equestris	59	583.1	1684.4
Stichopus horrens	1	13.5	139.5
Stichopus variegatus	1	93.7	1059.6
Ascidians			
Aplidium - sandy	1	113.0	1409.6
Aplidium sp.1	2	36.1	419.4
Aplidium sp.2	6	120.3	632.6
Ascidia scaevola	14	185.1	1866.3
Ascidia sydneiensis	23	89.0	262.9
Ascidian (mixed spp.)	5	173.4	899.8
Ascidian sp.1	24	33.1	129.3
Ascidian sp.2	3	0.6	3.6
Botrylloides sp.	1	0.1	1.2
Cemidocarpa stolonifera	9	44.9	192.0
Clavelina fecunda	6	10.3	70.0
*Condominium*sp.	5	142.5	1044.0
*Cystodytes*sp.	1	0.2	3.1
Didemnid sp.1	3	7.8	65.5
Didemnid sp.10	1	6.7	83.6
Didemnid sp.11	1	1.9	24.1

Species	%	Catch rate (g h^{-1})	s.d.
Didemnid sp.12	1	0.3	3.4
Didemnid sp.14	1	0.8	8.2
Didemnid sp.16	4	11.9	115.9
Didemnid sp.18	1	0.2	2.7
Didemnid sp.19	2	1.4	12.5
Didemnid sp.2	4	6.0	63.3
Didemnid sp.20	1	4.4	51.5
Didemnid sp.21	1	1.0	10.5
Didemnid sp.22	1	0.7	8.8
Didemnid sp.3	1	3.7	46.1
Didemnid sp.5	5	5.8	32.6
Didemnid sp.6	1	0.1	1.2
Didemnid sp.7	4	2.4	17.2
Didemnid sp.8	4	6.3	49.6
Didemnid sp.9	2	7.3	63.9
Didemnum molle	1	1.7	15.2
Hartmeyeria formosa	1	6.0	72.5
Herdmania momus	26	381.2	2174.1
Hypodistoma deerratum	20	282.2	1132.4
Microcosmus exasperatus	12	41.9	340.5
Microcosmus helleri	12	185.1	1266.4
Molgulid sp.	3	2.2	17.9
Perophora sp.	4	32.9	235.0
Phallusia millari	38	201.2	442.7
Polycarpa chinensis	20	19.1	63.0
Polycarpa olitoria	3	6.7	45.0
Polycarpa papillata	24	47.6	174.2
Polycarpa pigmentata	4	156.7	1622.4
Polycarpa procera	1	0.2	1.9
*Polycitor*sp.	1	1.1	13.3
Polyclinum sp.	4	25.6	170.1
Pseudodistoma sp.	18	118.6	487.2
Pyura obesa	3	3.9	26.7
Pyura sacciformis	12	63.5	248.9
Rhodosoma turcicum	1	0.2	2.6
Rhopalaea tenuis	11	10.0	60.6
Sigillina cyanea	1	1.3	11.8
Sycozoa sp.	1	0.3	2.7
Sipunculids			
Sipunculus sp.	1	0.1	0.7

Table App.2.D.2 Frequency of occurrence of the most common benthos categories of at least 40 animals in each cross-shelf stratum (*n* = the total number of individuals or colonies sampled)

	PCT OCCURRENCE DREDGE					
			Stratum Mean			
Class and Species	**A**	**B**	**C**	**D**	**E**	**Total No.**
Algae	15	.	13	25	29	
Sponge	93	95	94	71	76	
Hydrozoan	50	18	39	54	62	
Hydroid 19	.	3	.	4	.	1036
Hydroid 3	.	.	10	17	5	300
Hydroid 5	20	5	13	21	14	340
Hydroid 6	8	.	.	13	5	132
Hydroid 9	40	13	26	54	48	610
Pennatulacea	18	18	16	29	14	
Gorgonacea	30	25	26	21	43	
Zoantharia	85	80	100	100	95	
Flabellum sp.	30	63	65	17	10	515
Fungia sp. 1	18	.	71	83	71	7183
Fungia sp. 3	.	.	.	29	43	1347
Fungia sp. 4	10	.	32	8	10	656
Sphaenopus sp. 1	73	73	94	92	67	10240
Alcyonacea	88	83	77	88	81	
Alcyonarian 1	48	38	32	50	33	605
Alcyonarian 10	28	45	29	8	5	126
Alcyonarian 11	28	23	45	33	5	132
Alcyonarian 14	.	.	.	13	.	123
Alcyonarian 16	3	.	.	8	10	191
Alcyonarian 18	.	13	10	13	5	138
Alcyonarian 19	5	5	19	13	5	148
Alcyonarian 2	3	8	10	29	29	119
Alcyonarian 3	43	35	19	17	10	248
Alcyonarian 4	25	30	29	29	5	212
Alcyonarian 8	13	25	32	25	19	281
Crustacea	98	100	100	100	81	
Calappa terraereginae	53	60	6	8	.	138
Dardanus imbricata	23	15	52	38	10	193
Diogenes sp. 3	15	18	10	17	.	101
Hyastenus sp. 4	8	10	39	8	10	108
Leucosia ocellata	45	35	10	.	.	103
Matuta inermis	.	.	6	29	5	371
Metapenaeopsis palmensis	38	40	19	4	14	153
Penaeus esculentus	35	38	13	.	.	109
Portunus gracilimanus	50	48	6	.	.	118
Portunus rubromarginatus	50	70	65	33	24	318
Portunus tenuipes	53	68	48	17	10	622
Striped Hermit Crab	3	.	10	21	10	214
Thalamita bouveri	.	.	.	8	5	114
Gastropod	93	88	97	88	71	
Bivalvia	100	100	94	96	57	
Amusium pleuronectes	83	85	6	4	.	738
Amussiidae	13	3	.	.	.	106
Antigonia lamellaris	53	58	10	.	.	125

PCT OCCURRENCE DREDGE

	Stratum Mean					
Class and Species	**A**	**B**	**C**	**D**	**E**	**Total No.**
Bassina calophylla	43	80	13	.	.	650
Dosinia altenai	28	75	10	.	.	241
Fragum retusum	15	.	26	25	.	130
Melaxinia vitrea	48	80	42	8	.	424
Pinctada fucata	3	.	13	8	19	185872
Pinctada maculata	.	.	.	4	.	1850
Spondylus wrightianus	25	35	26	.	.	137
Vepricardium multispinosum	28	50	.	.	.	103
Cephalopod	30	55	32	38	10	
Bryozoa	68	60	77	83	81	
Bryozoan 11	.	10	.	17	.	255
Bryozoan 18	10	5	16	8	5	206
Bryozoan 2	.	.	10	25	10	441
Bryozoan 23	5	8	52	25	33	720
Bryozoan 24	.	.	.	13	.	183
Bryozoan 34	.	.	3	4	.	167
Bryozoan 6	28	25	13	17	14	259
Bryozoan 8	5	5	19	21	10	163
Bryozoan 9	13	5	26	54	29	272
Retiflustia cornea	28	3	13	17	33	154
Scrupocellaria sp.	23	5	6	17	14	221
Triphyllozoon sp.	10	5	35	29	38	223
Crinoid	75	65	97	92	100	
Asteroid	98	98	100	96	62	
Echinoid	98	100	100	100	81	
Holothuria	85	88	71	58	48	
Holothuria ocellata	60	50	6	.	5	155
Pentacta anceps	20	53	35	4	10	169
Ophiuroidia	53	58	84	96	71	
Brittle star 1	25	28	45	50	24	348
Brittle star 34	.	.	13	79	33	517
Ascidiacea	98	98	74	58	76	
Aplidium sp. 2	3	.	3	17	14	134
Ascidia scaevola	13	18	6	29	10	196
Ascidia sydneiensis	43	48	3	.	.	199
Ascidiacea	10	8	3	.	.	510
Ascidian 1	38	55	3	.	.	371
Clavelina fecunda	10	8	6	.	.	750
Condominium sp	.	3	.	13	19	286
Herdmania momus	38	43	23	8	5	727
Microcosmus exasperatus	15	8	16	8	14	140
Microcosmus helleri	23	18	10	.	.	939
Perophora sp.	.	.	.	8	19	6418
Phallusia millari	48	73	35	4	.	402
Polycarpa chinensis	28	38	6	8	10	190
Polycarpa papillata	35	35	13	17	10	235
Polycarpa pigmentata	3	.	10	4	10	135
Pseudodistoma sp.	18	45	3	4	5	370
Rhopalaea tenuis	28	10	.	8	5	435
Marine plant	5	.	.	.	5	

Table App.2.D.3 The mean biomass of species (and classes) of benthos caught at each station in each stratum during the two survey cruises in the Far Northern Section of the Great Barrier Reef, where at least 100 individuals were caught.

MEAN WEIGHT OVERALL PER STN IN KGS

			Stratum			
Class and Species	**A**	**B**	**C**	**D**	**E**	**Total No.**
Algae	0.02	0	0.39	11.85	1.13	
Panfera	2.45	4.31	1.47	13.84	1.45	
Hydrozoa	0.13	0.06	0.05	0.16	0.05	
Hydroid 19	0	0.002	0	0.003	0	1036
Hydroid 3	0	0	0.001	0.006	0	300
Hydroid 5	0.001	0	0	0.001	0.001	340
Hydroid 6	0.006	0	0	0.001	0	132
Hydroid 9	0.108	0.057	0.047	0.149	0.044	610
Pennatulacea	0	0	0	0.01	0.01	
Gorgonacea	0.03	0	0.01	1.15	0.17	
Zoantharia	0.23	0.32	2.73	2.87	5.15	
Flabellum sp.	0.006	0.033	0.029	0.005	0.003	515
Fungia sp. 1	0.048	0	1.058	0.4	0.208	7183
Fungia sp. 3	0	0	0	0.248	0.15	1347
Fungia sp. 4	0.011	0	0.301	0.005	0.064	656
Sphaenopus sp. 1	0.148	0.289	0.784	0.58	0.242	10240
Alcyonacea	0.16	0.17	0.72	0.79	0.38	
Alcyonarian 1	0.016	0.011	0.019	0.084	0.087	605
Alcyonarian 10	0.03	0.012	0.017	0.004	0.001	126
Alcyonarian 11	0.011	0.007	0.018	0.022	0.002	132
Alcyonarian 14	0	0	0	0.044	0	123
Alcyonarian 16	0	0	0	0.029	0.145	191
Alcyonarian 18	0	0.035	0.014	0.051	0.003	138
Alcyonarian 19	0.002	0.023	0.066	0.038	0.004	148
Alcyonarian 2	0	0.005	0.023	0.111	0.045	119
Alcyonarian 3	0.007	0.028	0.003	0.128	0.002	248
Alcyonarian 4	0.006	0.009	0.015	0.028	0.001	212
Alcyonarian 8	0.003	0.025	0.056	0.071	0.012	281
Crustacea	0.2	0.4	0.49	0.28	0.05	
Calappa terraereginae	0.009	0.017	0.002	0.004	0	138
Dardanus imbricata	0.002	0	0.006	0.003	0.001	193
Diogenes sp. 3	0	0	0.001	0	0	101
Hyastenus sp. 4	0.007	0.01	0.077	0.035	0.002	108
Leucosia ocellata	0.005	0.005	0.002	0	0	103
Matuta inermis	0	0	0.096	0.084	0	371
Metapenaeopsis palmensis	0.003	0.003	0.002	0	0.001	153
Penaeus esculentus	0.024	0.054	0.022	0	0	109
Portunus gracilimanus	0.009	0.01	0.001	0	0	118
Portunus rubromarginatus	0.02	0.052	0.071	0.044	0.014	318
Portunus tenuipes	0.021	0.099	0.054	0.002	0.007	622
Striped Hermit Crab	0	0	0.002	0.002	0.001	214
Thalamita bouveri	0	0	0	0.008	0	114
Gastropod	0.11	0.28	0.26	0.37	0.56	
Bivalvia	0.48	0.54	2.3	1.08	0.98	
Amusium pleuronectes	0.062	0.127	0.004	0	0	738
Amussiidae	0.019	0.001	0	0	0	106

MEAN WEIGHT OVERALL PER STN IN KGS

			Stratum			
Class and Species	**A**	**B**	**C**	**D**	**E**	**Total No.**
Antigonia lamellaris	0.008	0.018	0.001	0	0	125
Bassina calophylla	0.013	0.07	0.001	0	0	650
Dosinia altenai	0.012	0.037	0.001	0	0	241
Fragum retusum	0.002	0	0.011	0.002	0	130
Melaxinia vitrea	0.01	0.069	0.015	0.001	0	424
Pinctada fucata	0.191	0	1.99	0.31	0.948	18587
Pinctada maculata	0	0	0	0.484	0	185
Spondylus wrightianus	0.017	0.019	0.014	0	0	13
Vepricardium multispinosum	0.003	0.008	0	0	0	10
Cephalopod	0.03	0.12	0.02	0.02	0	
Bryozoa	0.06	0.08	0.53	0.72	0.12	
Bryozoan 11	0	0.001	0	0.1	0	255
Bryozoan 18	0.015	0.012	0.021	0.284	0.038	206
Bryozoan 2	0	0	0.264	0.023	0.001	441
Bryozoan 23	0.001	0.006	0.049	0.142	0.016	720
Bryozoan 24	0	0	0	0.012	0	183
Bryozoan 34	0	0	0.017	0.001	0	167
Bryozoan 6	0.003	0.05	0.001	0.028	0.003	259
Bryozoan 8	0.006	0.001	0.093	0.014	0.013	163
Bryozoan 9	0.007	0.003	0.009	0.023	0.008	272
Retiflustia cornea	0.002	0	0.002	0.004	0.005	154
Scrupocellaria sp.	0.005	0	0.002	0.028	0.006	221
Triphyllozoon sp.	0.001	0.001	0.025	0.012	0.008	223
Crinoid	0.1	0.14	1.58	4.35	5.5	
Asteroid	0.55	0.38	2.06	0.93	0.09	
Echinoid	0.92	6.65	0.42	0.05	0.06	
Holothuria	0.18	0.22	2.57	0.82	1.27	
Holothuria ocellata	0.037	0.046	0.004	0	0.003	155
Pentacta anceps	0.007	0.019	0.015	0.01	0.003	169
Ophiuroidea	0	0.01	0.03	0.22	0.09	
Brittle star 1	0.001	0.002	0.01	0.02	0.001	348
Brittle star 34	0	0	0.002	0.075	0.017	517
Ascidiacea	0.71	0.73	0.43	0.83	0.53	
Aplidium sp. 2	0.001	0	0.003	0.12	0.081	134
Ascidia scaevola	0.005	0.008	0.002	0.273	0.005	196
Ascidia sydneiensis	0.045	0.041	0.002	0	0	199
Ascidiacea	0.063	0.099	0.01	0	0	510
Ascidian 1	0.006	0.027	0	0	0	371
Clavelina fecunda	0.006	0.002	0.002	0	0	750
Condominium sp	0	0.013	0	0.048	0.186	286
Herdmania momus	0.242	0.103	0.026	0.015	0.002	727
Microcosmus exasperatus	0.008	0.002	0.003	0.003	0.052	140
Microcosmus helleri	0.146	0.027	0.011	0	0	939
Perophora sp.	0	0	0	0.03	0.027	6418
Phallusia millari	0.044	0.129	0.03	0.003	0	402
Polycarpa chinensis	0.005	0.012	0.001	0.002	0.001	190
Polycarpa papillata	0.01	0.017	0.003	0.01	0.021	235
Polycarpa pigmentata	0.001	0	0.184	0.005	0.015	135
Pseudodistoma sp.	0.015	0.091	0.007	0.008	0.001	370
Rhopalaea tenuis	0.007	0.003	0	0	0	435
Marine plant	0	0	0	0	0.02	

Table App.2.D.4 The mean number of species (and classes) of benthos caught at each station in each stratum during the two survey cruises in the Far Northern Section of the Great Barrier Reef, where at least 100 individuals were caught.

	MN NO OVERALL PER STN					
			Stratum Mean			
Class and Species	**A**	**B**	**C**	**D**	**E**	**Total No.**
Algae	0	0	1	1	2	
Panfera	11	10	19	117	17	
Hydrozoa	9	1	5	98	6	
Hydroid 19	0	0	0	65	0	1036
Hydroid 3	0	0	1	11	1	300
Hydroid 5	2	0	1	7	1	340
Hydroid 6	2	0	0	1	1	132
Hydroid 9	3	1	2	15	3	610
Pennatulacea	0	0	1	1	1	
Gorgonacea	1	1	2	13	2	
Zoantharia	18	28	358	234	115	
Flabellum sp.	1	6	6	1	1	515
Fungia sp. 1	5	0	176	48	22	7183
Fungia sp. 3	0	0	0	37	34	1347
Fungia sp. 4	1	0	20	0	1	656
Sphaenopus sp. 1	9	22	153	138	52	10240
Alcyonacea	8	12	18	53	7	
Alcyonarian 1	2	2	2	12	3	605
Alcyonarian 10	1	1	1	0	0	126
Alcyonarian 11	1	0	2	1	0	132
Alcyonarian 14	0	0	0	5	0	123
Alcyonarian 16	0	0	0	7	1	191
Alcyonarian 18	0	1	0	4	0	138
Alcyonarian 19	0	1	3	1	0	148
Alcyonarian 2	0	0	0	4	1	119
Alcyonarian 3	1	2	0	4	0	248
Alcyonarian 4	0	1	3	2	0	212
Alcyonarian 8	0	2	2	6	0	281
Crustacean	24	32	48	45	17	
Calappa terraereginae	1	2	0	0	0	138
Dardanus imbricata	1	0	4	1	0	193
Diogenes sp. 3	0	0	2	1	0	101
Hyastenus sp. 4	0	0	2	2	0	108
Leucosia ocellata	1	1	0	0	0	103
Matuta inermis	0	0	6	8	0	371
Metapenaeopsis palmensis	1	1	1	0	1	153
Penaeus esculentus	1	1	0	0	0	109
Portunus gracilimanus	2	1	0	0	0	118
Portunus rubromarginatus	1	3	3	2	1	318
Portunus tenuipes	2	9	6	0	0	622
Striped Hermit Crab	0	0	4	3	1	214
Thalamita bouveri	0	0	0	4	1	114
Gastropod	16	17	52	26	10	
Bivalvia	92	61	4517	1041	1106	
Amusium pleuronectes	6	12	0	0	0	738
Amussiidae	3	0	0	0	0	106
Antigonia lamellaris	1	2	0	0	0	125

MN NO OVERALL PER STN

	Stratum Mean					
Class and Species	**A**	**B**	**C**	**D**	**E**	**Total No.**
Bassina calophylla	2	14	0	0	0	650
Dosinia altenai	2	5	0	0	0	241
Fragum retusum	1	0	3	1	0	130
Melaxinia vitrea	1	9	2	0	0	424
Pinctada fucata	61	0	4504	950	1104	18587
Pinctada maculata	0	0	0	77	0	1850
Spondylus wrightianus	2	1	1	0	0	137
Vepricardium multispinosum	1	2	0	0	0	103
Cephalopod	1	2	2	1	0	
Bryozoa	7	3	35	74	14	
Bryozoan 11	0	0	0	10	0	255
Bryozoan 18	0	0	1	6	1	206
Bryozoan 2	0	0	11	4	0	441
Bryozoan 23	0	0	6	21	2	720
Bryozoan 24	0	0	0	8	0	183
Bryozoan 34	0	0	5	0	0	167
Bryozoan 6	1	1	0	6	0	259
Bryozoan 8	0	0	3	1	1	163
Bryozoan 9	1	0	2	5	2	272
Retiflustia cornea	1	0	1	1	3	154
Scrupocellaria sp.	1	0	0	7	2	221
Triphyllozoon sp.	1	0	4	2	1	223
Crinoid	5	3	140	250	583	
Asteroid	17	37	31	21	6	
Echinoid	64	869	21	4	3	
Holothuria	3	6	6	6	1	
Holothuria ocellata	2	2	0	0	0	155
Pentacta anceps	0	2	1	1	0	169
Ophiuroidea	2	3	8	27	9	
Brittle star 1	1	1	5	6	1	348
Brittle star 34	0	0	1	17	5	517
Ascidiacea	66	56	22	153	182	
Aplidium sp. 2	0	0	0	5	1	134
Ascidia scaevola	0	1	0	5	0	196
Ascidia sydneiensis	2	3	0	0	0	199
Ascidiacea	3	8	3	0	0	510
Ascidian 1	1	8	0	0	0	371
Clavelina fecunda	10	4	5	0	0	750
Condominium sp	0	0	0	1	12	286
Herdmania momus	13	4	1	1	0	727
Microcosmus exasperatus	1	0	1	0	4	140
Microcosmus helleri	20	3	1	0	0	939
Perophora sp.	0	0	0	131	156	6418
Phallusia millari	3	5	2	0	0	402
Polycarpa chinensis	2	3	0	0	0	190
Polycarpa papillata	1	2	0	1	3	235
Polycarpa pigmentata	0	0	4	0	1	135
Pseudodistoma sp.	2	6	0	1	0	370
Rhopalaea tenuis	5	6	0	0	0	435

CHAPTER 3

COMPARISON OF ZONES CLOSED AND OPEN TO TRAWLING

Chapter Authors:

C. Burridge, R. Pitcher, T. Wassenberg and N. Gribble

CONTENTS

3 A COMPARISON OF THE FAUNA OF THE AREA CLOSED TO FISHING (GREEN ZONE) WITH AREAS OPEN TO FISHING

3 A COMPARISON OF THE FAUNA OF THE AREA CLOSED TO FISHING (GREEN ZONE) WITH AREAS OPEN TO FISHING

Objectives

There were two objectives in this part of the study:

- The first was to compare the benthic communities and fish communities in areas closed to trawling with those in areas open to trawling under GBRMPA Zoning Plans.
- The second was to compare the prawn communities of areas closed to trawling with areas open to trawling under the GBRMPA Zoning Plans.

These objectives were to be achieved by using the Cross Shelf Closure (Green Zone) in the Far Northern Section of the Great Barrier Reef Marine Park as the closed area and comparing it with the areas to the north and south of the Green Zone that are open to trawling. The study was to include an overall survey of the areas. The results of the survey are dealt with in Chapter 2. Here we deal only with differences between the open and closed areas that could either be a result of the presence or absence of trawling or might affect conclusions about the effects of trawling. There has been an unknown level of illegal trawling within the Green Zone. At the start of the study, and even now, there was an absence of high resolution spatial information on trawling in the open areas. Consequently this study is a comparison between an area that is closed to fishing with areas that are open to fishing, it is not a study of trawled and untrawled areas.

3.1 Introduction

The GBRMPA workshop (Craik et al, 1989) recommended that the study should take advantage of an area closed to trawling (Marine National Park B Zone) in the Far Northern Section of the GBR. This closure, commonly referred to as the Green Zone, consists of a cross-shelf strip of approximately 10 000 km^2 situated on a remote stretch of the northern coast of Queensland. It includes the inshore lagoon, inshore reefs and islands, mid–shelf shoal and reef zone and offshore lagoon, and is bordered to seaward by the ribbon reefs of the outer barrier. This closure is exceptionally large by world standards and comprises a complex variety of habitats. Initially the only data available on the distribution of trawling effort was on a 30-minute grid square basis. An additional complication was that the remoteness of the Green Zone made surveillance of the closure difficult and it was known that some illegal trawling had taken place although this was mostly concentrated in the lagoon between the mainland and the reef (Gribble and Robertson, 1998).

It was considered important that the study not be directed into simply comparing a few selected high fishing areas with the area closed to fishing. The trawl fishery associated with the Great Barrier Reef Heritage area operates over a range of complex habitats and the study was intended to study processes at the ecosystem level. The workshop specifically recommended against reductionist research and argued that a large scale experimental approach would ‘provide useful answers to effects of fishing at the scales with which we are dealing’. The intention of the research was to address the issue at scales that matched the scale of trawling and of the ecosystems that may be affected. That is, the research should attempt to encompass important ecological process and connections, especially those that may be affected by trawling. In practice, this meant the scale of the research should be as large as practical. The approach was to sample the cross-shelf closure and compare the species composition and abundance with that in adjacent areas to the north and south that were open to prawn trawling.

Initially, representative sampling (by area) using a benthic dredge, fish trawl and prawn trawl, was conducted in 1992 to describe the benthic, fish and prawn communities of the closed and adjacent open areas (see Chapter 2). The aim of this survey was to describe and characterise the demersal communities and the sediment composition of the study area. The sampling confirmed the value of the inter-reef communities in terms of their biodiversity (thousands of species, many or most of which are undescribed), representation of marine biological evolutionary history, and provision of habitat for many other organisms (Chapter 2). The results of the 1992 descriptive sampling also provided valuable information on which to base the design of the most cost-effective sampling strategies for, and estimate the power of, the 1993 sampling and the experiments described in Chapters 4 and 5. The types of information used in design included: the mean biomass of organisms in the closure area, the variance at a range of spatial scales, the time required to do various components of the sampling, and an indication of the possible effect size due to exposure to trawling. The aim of the second survey (1993) was to compare the communities in the closed zone with those in adjacent parts of the open zone to the north and south of it.

At the beginning of this study, there was a wide-spread perception that trawling was extremely damaging to the seabed environment and that effect sizes would be large, although rigorous quantitative information was scarce. The work of Sainsbury (1987) had been and continues to be, widely publicised. This reported results from surveys, conducted before and after Taiwanese pair-trawling on Australia's north west shelf, showing changes in catch rates of large sponges from ~500 kg hr^{-1} before trawling, down to ~5 kg hr^{-1} after. Research on the North West Shelf by CSIRO and subsequently reported in Sainsbury et al (1997) on video observations of the impact of ground gear on large sponges had shown that up to 90% of sponges were removed by the pass of a single trawl. Consequently, we anticipated designing for the capability to detect large effect sizes of 10-fold or less.

In this Chapter, we have examined two effects of interest. The primary one is the difference between the zone closed to trawling and the neighbouring zones open to trawling. The secondary one is the difference between the northern and southern parts of the open zone. These effects are likely to be more subtle than other sources of variation, and it was important to remove both large-scale (e.g. cross-shelf) variation and small-scale (e.g. depth and habitat) variation as effectively as possible.

For this reason, we used analysis of covariance. We fitted a model involving linear response to environmental variables such as sediment mud content and calcium carbonate content, water depth, an index of structured benthic habitat, and year-to-year variation (the covariates) in order to enhance the precision with which the two effects of interest could be assessed. We also included an index representing the three-dimensional complexity of the sea bottom and a variable representing lunar phase for the prawn data set.

3.2 Methods

3.2.1 *Study design (1993 Survey)*

General design issues

The design process involved setting the probability of type I (α) and type II (β) errors, where the former is the risk of falsely accepting the hypothesis that there is a difference between closed and open areas when there is none and the latter is the risk of falsely accepting the hypothesis that there is NO difference between closed and open areas when a difference exists. Having set α and power ($1-\beta$) at acceptable levels (often 0.05 and 0.80 respectively) it is possible to estimate the sample size required to detect a specified level of impact. Alternatively, given a specified sample size (usually due to resource limits), the level of detectable impact can be estimated. For this study, detectable effect-sizes were estimated, using non-central distribution functions implemented in the SAS statistical software (SAS, 1990; Muller et al., 1992; O'Brien and Muller, 1993).

Cohen (1988) introduced the concept of a standardised "effect-size index" (ESI). His aim was to define a dimensionless index that specifies an effect-size relative to the variance of a sample. For a test of two means:

(1) $$\underline{ESI} = \delta / \sigma$$ Cohen (1988)

where δ = difference between the means and σ = common population standard deviation. For example, a given effect may be considered large for a homogeneous population with a small variance, whereas the same effect maybe considered small for a heterogeneous population with a large variance. By examining the conclusions for a range of studies, Cohen derived some empirical guide-lines for his index: for a "small" effect, the ESI was ~0.1; for a "medium" effect, the ESI was ~0.25; and for a "large" effect, the ESI was ~0.4. As discussed in the introduction, the impacts of trawling were expected to be in the category of "large" effects.

During the descriptive sampling in the first year of this study, more than 1000 taxa were recorded from three different sampling gears (fish trawl, prawn trawl, epibenthic dredge). It was impractical to attempt to include all this information in the design process. The design calculations were based on the results of analysis of variance of taxon weights (log10 transformed) at the taxonomic class level and for the most wide-spread species (ie. those present in more than half the stations), and were done separately for each of the sampling gears. Because the species level power analysis covered only a small fraction of the data, it was considered that summarising at the taxonomic class level was the most appropriate way to cover the majority of the data for the power analysis. It has been shown that this type of summarisation still retains patterns in data, as many benthic species appear to respond similarly, at the class level, to impact due to their similar life habit eg. Warwick and Clarke, 1993).

The objective of the research reported in this Chapter was to compare the benthos, fish and prawn communities of the cross-shelf closure zone with those of adjacent areas where prawn trawling is permitted. Simply comparing one closed zone with open areas could be regarded as a pseudo-replicated design because there was only a single closure. While this may be a philosophically correct attitude if the aim was to generalise more widely to all closed zones, the fact remains that there was only one closure zone. Further, the intention was also to provide feedback to managers on the outcomes from a given closure declaration. It was not possible to compare trawled and non-trawled areas per se, because at the time of the survey design, information on trawl effort distribution was inadequate for any reliable stratification. Consequently, sampling stations were to be distributed randomly throughout both closed and open areas without stratification according to trawling effort — there were areas outside the closure that were unlikely to have been trawled and there was evidence that significant illegal trawling had continued in the closure subsequent to the declaration (Gribble and Robertson, 1998). It was considered that should the effort data become available it may be used as a covariate for post hoc analysis at a later date.

Design principles

The objective of the closed vs open comparison and general sampling design principles dictated the following:

- The main effect of interest was Zones, with 2 levels (open, closed). The "open" samples were to be taken from areas adjacent to the closure area both to the north and south, to minimise the risk of spatial variation compromising the interpretation, but treated together as a contrast with "closed" to simply estimate power and effect sizes.

- Variance due to cross-shelf habitat differences should be partitioned as a second main effect (ie. Strata, as in the descriptive study), not only because they are of interest but because such partitioning will improve the variance of the means for the Zones.

- To achieve greatest power for the amount of sampling effort, there should be balanced distribution of stations across closed and open zones and across the cross-shelf habitat strata; i.e. equal replication in all cells of the design.

The mid-shelf inter-reefal/shoal stratum is of major interest to the effects of fishing issue because, unlike the inshore lagoon, this stratum remains untrawled in many areas of the GBR, yet is attractive to fishermen because of the prevalence of valuable red-spot prawns — it is also attractive to conservationists and the GBRMPA as an ecologically diverse inter-reefal habitat. In the descriptive study, this stratum was about twice as wide as the other three, but in this design this stratum was divided equally to form a fifth stratum so that numerically balanced sampling in all cells would also be more representative in terms of area sampled (Table 3.01).

Table 3.01 Design of sampling strategy for comparing Open and Closed zones across habitat strata A–E. Strata are as follows: inshore lagoon (A), inshore reefs and islands (B), inshore reef-shoal matrix (C), offshore reef-shoal matrix (D) and outer lagoon (E). In the final design, n=10 stations per cell.

Zone	**Stratum**					**Total**
	A	B	C	D	E	Σ
Open(N&S)	n	n	n	n	N	$5n$
Closed	n	n	n	n	N	$5n$
Σ	$2n$	$2n$	$2n$	$2n$	$2n$	$10n$

Cost-benefit analysis

Prior to estimation of power, cost-benefit analysis was conducted of the spatial hierarchical sampling used in the descriptive study where there were two random sampling stations nested within random locations of area about 13 n.mile^2. Each cell of the main factors of the descriptive study design (3 zones × 4 strata = 12 cells) contained a number of locations proportional to the area of the cell. This nesting of stations within locations for each cell was necessary to estimate the variances at a range of spatial scales so that sampling effort could be optimally distributed among spatial scales according to the level of variability and the cost of sampling at each scale. The optimization formula used was:

(2) $$\text{Number of Stations per Location} = \sqrt{\frac{c_L \cdot s_S^2}{c_S \cdot s_L^2}}$$ (Snedecor & Cochran, 1967)

where c is the cost (time) of sampling locations (L) and stations (S), i.e. ~0.7 hrs and ~2.5 hrs, respectively and the s^2 are the associated variances. The location variance was estimated from the results of analysis of variance of the initial survey data as:

(3) $$s^2_L = (\underline{MS}_{L(ZS)} - \underline{MS}_e)/n$$ (Underwood, 1981)

where $\underline{MS}_{L(ZS)}$ = mean-square of locations nested in zone and stratum, $\underline{MS}_e$ = mean-square error and $n = 2$ stations per location.

The cost-benefit analysis was conducted for 8 prawn species, 15 bycatch classes and 32 bycatch species sampled by the prawn trawler; 15 fish families and 38 fish species sampled by the fish trawler; and 15 invertebrate classes and 17 species sampled by the benthic dredge. Overall, the most frequent options across the 3 gears, taxonomic classes and species were either one station per location or simple random sampling (ie. drop locations — see below). In practice, these two alternatives were identical.

Minimum detectable differences

Although the design was two factor (Zone and Stratum), for the power analysis it was necessary to examine only the differences between the level means for the open and closed areas, without affecting its applicability. Further, because the design was fully orthogonal and there were only two levels for Zone (open, closed), the power analysis could be treated as a t-test of the level means for the factor Zone. We wished to detect whether some fauna were more abundant in trawled areas, as well as those that may be negatively impacted, so the test was 2-tailed. The fact that another factor (Stratum) was in the design is accounted for by the reduced degrees of freedom for Zone in the factorial design compared with a simple two sample case.

Power analysis was then used to estimate the minimum detectable differences that could be achieved with different numbers of stations. For the proposed closed vs open comparison, variances were required as input for a priori power calculations. However, because the cost-benefit analysis showed that the sampling hierarchy should be changed from two-stations-per-location to one-station-per-location, the location mean square was re-estimated, and used as the sample variance, as:

(4) $$\underline{MS}_{L(ZS)} = n.s^2_L + s^2_e$$ (see Underwood, 1981)

where $n = 1$ station/location. In cases where $\underline{MS}_{L(ZS)} \leq \underline{Ms}_e$ from ANOVA, a pooled error mean square was used as the sample variance, and estimated as:

(5) $$\underline{MS}_{Pooled} = (\underline{SS}_{L(ZS)} + \underline{SS}_e)/(\underline{df}_{L(ZS)} + \underline{df}_e).$$

Given the available resources, it was estimated that the maximum possible number of sampling stations was about 100. The minimum difference (δ) between the open and closed zones that could be detected by a design with ~100 stations was given by a re-arrangement of the equation for the non-centrality parameter (γ) for the t-distribution (with equal sample size n' = 50 for each zone):

(6) $$\delta = \sqrt{\frac{2 \cdot \gamma^2 \cdot s^2}{n'}}$$ SAS (1990)

where s^2 = pooled estimate of the common variance from the descriptive study. In this case, γ was chosen to give power (1-β) of 0.80 by iterating the SAS function PROBT.

For a two-tailed test of effects in either direction, power was evaluated as follows:

(7) $$\text{Power} = \text{PROBT}(-T,\nu,\gamma) + 1\text{-PROBT}(T,\nu,\gamma)$$

where T = critical value of the t-distribution for $\alpha = 0.05$, ν = degrees of freedom for zones (= 90, for 100 stations). For a two-tailed test, T was evaluated with the SAS TINV function as follows:

(8) $$T = \text{TINV}(1\text{-}\alpha/2,\nu)$$

Cost-benefit analysis

The cost-benefit analysis was conducted for 145 cases, comprising classes and taxa sampled by the prawn trawler, fish trawler and the benthic dredge (results for each case are shown in Appendix 3.A). Overall, by far the most frequent option (70% of cases) across the 3 gears was one station per location (Table 3.02) and this was clearly the most appropriate choice for the Closed vs open sampling. Cases for 0 stations per location were, in practice, the same as one station per location. Cases for 2 stations per location were unlikely to be sub-optimally sampled by a strategy of one station per location. The number of cases where ≥ 2 stations per location were indicated was not significant. In 25 of 145 cases, the location level was essentially zero (because $MS_{L(ZS)} - MS_e \leq 0$), indicating that locations should be omitted from the design — ie. sampling should be simply random within cells. In practice, this is essentially the same as sampling one station per location and these cases were tabulated as such in Table 3.02.

Table 3.02 Summary table of closed vs open cost-benefit analysis showing optimal (integer) number of stations per location.

Taxa group	Number of stations per location										Number of cases
	mean	0	1	2	3	4	5	6	7	8	
Prawn species	0.53	5	3								8
Prawn bycatch classes	1.43	2	10	4				1			17
Prawn bycatch species	0.80	6	23	3							32
Fish trawl families	0.79	2	12	1							15
Fish trawl species	1.22	4	29	2		2				1	38
Benthic dredge classes	1.24	1	11	1	2	1					16
Benthic dredge species	1.07		14	2	3						19
Total	1.01	20	102	13	5	3	0	1	0	1	145

Minimum detectable differences

The sample variances for each class or species, re-estimated because the cost-benefit analysis showed that the sampling hierarchy should be changed from two-stations-per-location to one-station-per-location, are shown in Appendix 3.A.

For the purpose of estimating minimum detectable differences (δ) between the open and closed zones, initially for a design with ~100 stations, the appropriate two-tailed critical value of the t-distribution was $T = 1.987$ for $\alpha = 0.05$ and degrees of freedom $\nu = 90$ (note that for a simple 2-sample t-test, $\nu = 98$). For a power of $(1-\beta) = 0.80$, the corresponding two-tailed value of the non-centrality parameter was $\gamma = 2.832$. In this case, the overall average estimate of minimum detectable difference (δ) between the open and closed zones (with equal sample size n' = 50 for each zone) that could be detected was a reduction in biomass in one zone down to less than ~40% relative to the other zone, and vice-versa (Table 3.03). Average minimum detectable effects ranged from a reduction to ~36% for fish families to reduction to 54% for prawn bycatch (Table 3.03). For individual cases, minimum detectable effects ranged from a reduction to ~13% for sponges caught as bycatch in prawn trawls to a reduction to ~91% for the classes polychaetes, gastropods and bryozoans caught as bycatch in prawn trawls. Over all taxa, the 66 percentile range of minimum detectable effects was a reduction to 29–54% (results for each case are shown in Appendix 3.A). In each case, Cohen's Effect-Size Index was 0.283, corresponding to a medium-large detectable effect.

Table 3.03 Summary of minimum detectable effect-size, δ, for comparing closed and open zones. This has been converted to a relative biomass ratio (expressed as a percentage). Cohen's Effect-Size Index was 0.283 in each case.

Taxa group	δ	**relative biomass (%)**
Dredge Class averages	0.451	37.0
Dredge species averages	0.423	38.5
Prawn bycatch class average	0.310	54.2
Prawn bycatch species average	0.350	45.3
Fish trawl family average	0.449	36.4
Fish trawl species average	0.422	39.0
Prawn species average	0.402	40.7
Overall	0.400	39.8

In all cases tested, across all three sampling gears, the power analysis showed that the largest feasible survey (ie. within the available resources) was more than capable of meeting both effect-size criteria. That is, capable of detecting a "large" effect (sensu Cohen 1988) and a 10-fold reduction in biomass (ie. down to <10%). Surveys with fewer sampling stations were not specifically examined, nevertheless it was possible that fewer than 100 stations might get sampled due to weather or seabed conditions — if the sample size fell short by as many as 20 stations, the overall average estimate of minimum detectable difference was a reduction to <~35%, or an ESI ~ 0.32.

Differences of this magnitude were considered likely given that survey data from areas such as the Northwest Shelf have indicated 10-fold to 100-fold reductions in benthos bycatch — which could be considered virtual complete removal of sponges and other epibenthos (see introduction). Again, these differences were not unreasonable to expect and it was considered that the sampling design will have adequate power to detect somewhat less than order-of-magnitude changes in benthos biomass.

3.2.2 Field Sampling Methods

The survey to compare closed and open zones involved sampling with the chartered fish trawler *Clipper Bird* and the QDPI prawn trawler *Gwendoline May*. The fish trawler sampled throughout daylight hours and the prawn trawler throughout the night. The fish trawler used a Frank and Bryce fish trawl net, a Church dredge and a video sled, and the prawn trawler used two Florida Flyer prawn trawl nets. The video sled was deployed from the port side of the fish trawler at the same time as the dredge was deployed from the starboard side. The duration of the tows was generally between 15 and 30 minutes depending on the device, at between two and three knots (1–1.5 m/s). Sampling for the *Clipper Bird* commenced on 22 March 1993 and ended on 15 April 1993. Sampling for the *Gwendoline May* took place from 7-15 March, 24 March-1 April and 25 May-7 June 1993. The spatial positions of sites for 1992, 1993 are shown in Figure 2.14 a,b. Full details of year and field sampling techniques are given in Chapter 2 (Section 2.8.2).

3.2.3 Data preparation and statistical analysis

Data sets

Data collection methods are described in Section 2.8.2 (Chapter 2). Four data sets have been analysed for this Chapter:

1. prawn species from the prawn trawl

2. the bycatch (fish and invertebrates) from the prawn trawl

3. the fish species found in the fish trawl and prawn trawl data

4. the invertebrates from the benthic dredge

For each data set, the weight and number of animals per species (grossed up, as described in Section 2.8.2, where a subsample of the catch was taken) were analysed. The catch was standardised to weight or number per half hour for fish and bycatch; and weight or number per quarter hour for the benthic dredge; reflecting the typical tow duration for each sampling device. For prawns, the catch was standardised to weight or number per hectare because this is more commonly used.

Tows were planned to be of a standard duration (30 minutes for fish and prawn trawlers, 15 minutes for the dredge). However, operational difficulties such as gear problems or rough round sometimes caused a tow to be shorter than planned. Catch in shorter tows may not be representative of catch in longer tows, so some tows were excluded from analysis. For prawns it was not considered necessary to exclude tows because prawns are caught only at the point where they are encountered. Fish, however, can swim for some time in front of the net and may only be captured when they become tired. The prawn trawl tends to catch smaller fish species, so only tows of less than 11 minutes were excluded. The fish trawl tends to catch larger fish species, so tows of less than 15 minutes were excluded. Most organisms caught by the dredge are either sessile or slow-moving, but the species are known to have a very patchy distribution so tows of less than 7 minutes were excluded. This left 126 stations for the prawns in the prawn trawl; 122 stations for bycatch; 149 stations for the fish trawl and 157 stations for the dredge. Tables 3.04 and 3.05 show which devices were successfully deployed at each station together with the zone for that station. Rough bottom was usually the reason for gear not being successfully deployed at a given station.

We used biological data from the 1992 (descriptive) and the 1993 (closed vs open) surveys to compare the communities in the zones closed and open to trawling. There is a strong advantage in doing so because the combined data set provides a more powerful tool for assessing differences in communities that are highly variable. It was possible to combine the data from both surveys because the location level variation was negligible and thus the 1992 data could be treated as if it was sampled with the same hierarchy as 1993 data, without compromising the interpretation of the analyses. For the purposes of analysis, the combined dataset is regarded as a random distribution of sampling sites across the study area. Further, the use of analysis of covariance, with the environment characterised by a suite of covariates for each station, rendered unimportant the fact that the first survey had a pair of stations at each location whereas the second survey had one station per location.

Table 3.04 Major activities carried out by zone, during the initial survey cruise, in the far northern section of the GBR (1992). The + sign indicates that the activity was carried out successfully. The – sign indicates that deployment was unsuccessful or not attempted.

Station	Dredge	Fish trawl	Prawn trawl	Zone	Station	Dredge	Fish trawl	Prawn trawl	Zone
001	+	+	+	Open N	051	+	+	+	Closed
002	+	+	+	Open N	052	+	+	+	Closed
003	+	+	+	Open N	053	+	–	–	Closed
004	+	+	+	Open N	054	+	+	–	Closed
005	+	+	+	Open N	055	–	–	–	Closed
006	+	+	+	Open N	056	–	–	–	Closed
007	+	+	+	Open N	057	–	–	–	Closed
008	+	+	+	Open N	058	+	–	–	Closed
009	+	+	+	Open N	059	–	–	–	Closed
010	+	+	+	Open N	060	+	+	–	Closed
011	+	+	+	Open N	061	+	–	–	Closed
012	+	+	+	Open N	062	+	–	–	Closed
013	–	–	–	Open N	063	+	–	–	Closed
014	–	–	–	Open N	064	+	–	–	Closed
015	+	+	–	Open N	065	+	–	–	Closed
016	+	+	–	Open N	066	+	+	–	Closed
017	+	+	–	Open N	067	+	+	–	Closed
018	+	–	–	Open N	068	+	+	–	Closed
019	+	+	+	Open N	069	+	–	–	Closed
020	+	+	+	Open N	070	+	+	–	Closed
021	+	+	+	Open N	071	+	–	–	Closed
022	+	+	+	Open N	072	+	–	–	Closed
023	+	–	–	Open N	073	+	–	–	Closed
024	+	+	–	Open N	074	+	+	+	Closed
025	+	+	–	Open N	075	–	–	–	Closed
026	+	–	–	Closed	076	–	–	–	Closed
027	+	+	+	Closed	077	–	–	–	Closed
028	+	+	+	Closed	078	–	–	–	Closed
029	+	+	+	Closed	079	–	–	–	Closed
030	+	+	+	Closed	080	–	–	–	Closed
031	+	+	+	Closed	081	+	+	–	Closed
032	+	+	+	Closed	082	+	+	–	Closed
033	+	+	+	Closed	083	–	–	–	Closed
034	+	+	+	Closed	084	+	+	–	Closed
035	+	+	+	Closed	085	–	–	–	Closed
036	+	+	+	Closed	086	+	+	–	Closed
037	+	+	+	Closed	087	+	–	–	Closed
038	+	+	+	Closed	088	+	–	–	Closed
039	+	+	+	Closed	089	+	+	–	Closed
040	+	+	+	Closed	090	+	–	–	Closed
041	+	+	+	Closed	091	+	+	+	Open S
042	+	+	+	Closed	092	+	+	+	Open S
043	+	+	+	Closed	093	+	+	+	Open S
044	+	+	+	Closed	094	+	+	+	Open S
045	+	+	+	Closed	095	+	+	+	Open S
046	+	+	+	Closed	096	+	+	+	Open S
047	+	+	+	Closed	097	+	+	–	Open S
048	+	+	+	Closed	098	+	+	–	Open S
049	+	+	+	Closed	099	+	–	–	Open S
050	+	+	+	Closed	100	+	–	–	Open S

Table 3.05 Major activities carried out by zone, during the Open versus Closed survey (1993), in the far northern section of the GBR. The + sign indicates that the activity was carried out successfully. The – sign indicates that deployment was unsuccessful or not attempted.

Station	Dredge	Fish trawl	Prawn trawl	Zone	Station	Dredge	Fish trawl	Prawn trawl	Zone
001	+	+	–	Open S	051	+	+	+	Closed
002	+	+	–	Open S	052	+	+	+	Closed
003	+	+	+	Open S	053	+	+	+	Closed
004	+	+	+	Open S	054	+	+	+	Closed
005	+	–	–	Open S	055	+	–	–	Closed
006	+	+	+	Open S	056	+	+	+	Closed
007	+	–	–	Open S	057	+	+	+	Closed
008	+	+	–	Open S	058	+	+	+	Closed
009	+	+	–	Open S	059	+	+	+	Closed
010	+	+	+	Open S	060	+	–	+	Closed
011	+	+	–	Open S	061	+	–	–	Closed
012	+	+	–	Open S	062	+	+	+	Open N
013	+	–	–	Open S	063	+	–	–	Open N
014	+	–	–	Open S	064	+	–	–	Open N
015	+	–	–	Closed	065	+	+	+	Open N
016	+	+	+	Closed	066	+	+	+	Open N
017	+	+	+	Closed	067	+	+	+	Open N
018	+	+	+	Closed	068	+	+	+	Open N
019	+	+	+	Closed	069	+	–	+	Open N
020	+	–	–	Closed	070	+	–	+	Open N
021	+	+	+	Closed	071	+	+	+	Open N
022	+	+	+	Closed	072	+	+	+	Open N
023	+	+	+	Closed	073	+	–	–	Open N
024	+	+	+	Closed	074	+	+	+	Open N
025	+	–	–	Closed	075	+	+	+	Open N
026	+	–	–	Closed	076	+	+	+	Open N
027	+	+	+	Closed	077	+	+	+	Open N
028	+	+	+	Closed	078	+	+	+	Open N
029	+	+	+	Closed	079	+	+	+	Open N
030	+	–	–	Closed	080	+	+	+	Open N
031	+	+	+	Closed	081	+	+	+	Open N
032	+	+	+	Closed	082	+	+	+	Open N
033	+	+	+	Closed	083	+	+	+	Open N
034	+	+	+	Closed	084	+	+	+	Open N
035	+	+	+	Closed	085	+	+	+	Open N
036	+	+	+	Closed	086	+	+	+	Closed
037	+	+	+	Closed	087	+	+	+	Closed
038	+	+	+	Closed	088	+	+	+	Closed
039	+	+	+	Closed	089	+	+	+	Closed
040	+	+	+	Closed	090	+	+	+	Closed
041	+	+	+	Closed	091	+	+	+	Closed
042	+	+	+	Open S	092	+	+	+	Closed
043	+	+	+	Open S	093	+	+	+	Closed
044	+	+	+	Open S	094	+	+	+	Closed
045	+	+	+	Open S	095	+	+	+	Closed
046	+	+	+	Closed	096	+	+	+	Open S
047	+	+	+	Closed	097	+	+	+	Open S
048	+	+	+	Closed	098	+	+	+	Open S
049	+	+	+	Closed	099	+	+	+	Open S
050	+	+	+	Closed	100	+	+	+	Open S

Methods of analysis

The data sets were analysed by both univariate (single species) and multivariate (multi-species) analysis of covariance in a general linear model. For the univariate analysis, the significance of each term was assessed by the F statistic for the type II sum-of-squares; and an estimate of the coefficient for that covariate or factor of interest was extracted. Results for terms in the multivariate model were summarised by using Wilks' lambda and the associated F statistic (Mardia, Kent & Bibby, 1979). In the multivariate case, there should be no more than $n - q$ species in the data matrix, where q is the number of parameters in the model and n is the number of stations. Otherwise the error matrix would be singular (determinant of zero). In fact, the largest station by species matrix for each data set had about 20 species fewer than this limit, so the error matrix would not be ill-conditioned (determinant close to zero).

For univariate analysis we excluded those species that were found in less than 11 tows (fish community, bycatch and benthic invertebrates) or 6 tows (prawn species in prawn trawl). For an overall assessment of these results, we tabulated the percentage of species that had a significant result for each covariate and the two zone contrasts. We also calculated these percentages for each of three groups: the very common species that appeared in more than 40 stations; the common species that appeared in between 21 and 40 stations; and the less common species that appeared in between 11 and 20 stations.

For multivariate analysis, we formed a number of data sets for analysis. Each data set contained taxa with a similar frequency of occurrence. We formed five data sets for each sampling method: the species that appeared in at least 40 stations; those that appeared in at least 21 and at most 40 stations; the 11 to 20 range; the 6 to 10 range (7 to 10 for benthic invertebrates due to the large number of taxa); the 3 to 5 range (4 to 6 for benthic invertebrates); and finally the most comprehensive group consisting of all species appearing in at least 15 stations.

Analysis of covariance was performed with PROC GLM in SAS. The data were $\log_{10}$-transformed after adding a constant to compensate for zeros: half the smallest non-zero weight or number. The environmental covariates used were: mud content, calcium carbonate ($CaCO_3$) content, depth, a habitat index and year of sampling (1993 versus 1992). For prawns, two extra variables were included: lunar phase and rugosity of the seabed.

The habitat index was derived from the dredge data. A set of 28 "structural" species (from the classes Porifera and Cnidaria) were selected from the dredge data and their total weight $\log_{10}$-transformed. A weight of 1g was added to every sample in order to handle the presence of zeros. Where these species have been modelled by the analysis of covariance, there could be a much higher probability of a significant relationship with the habitat index simply because of the component of the index due to that species. Only four of the species used to calculate the habitat index were common enough for inclusion in the single-species analyses for the benthic invertebrate community. These species were: *Ianthella sp.*, Porifera sp.36, Gorgonia sp.3 and *Alcyonaria* sp.19. All four species had a significant relationship with the habitat index, but so did ten other of the 33 species of Porifera and Cnidaria that were analysed. The other 24 "structural" species form a small subset of the more than 200 rare species and would be expected to have little influence on significance levels in the multivariate analysis.

Lunar phase ('moon' in the model) was set to 0 for the week centred on full moon and 1 for the remaining three weeks of the month. A positive coefficient for lunar phase means that larger quantities of prawns are caught around new moon Rugosity was represented by the standard deviation of the depth along the path of each prawn trawl, recorded at intervals of 0.1 n.mile.

The three cross-shelf zones (north open, south open and the closed zone) were compared by using two contrasts. A contrast between the northern and southern open zones (denoted by NvS) was evaluated by setting up a dummy variable with the following values: north open = 1; south open = –1; and closed = 0 so the range was from –1 to 1. The estimated coefficient is the deviation of the north open zone from the mean of the two open zones. A contrast between the closed and open zones (denoted by CvO) was evaluated by setting up a dummy variable with a value of 1 for the closed zone and 0 for each open zone. The estimated coefficient is the deviation of the closed zone from the mean of the open zones.

The general linear model for Y=log-transformed weight, or Y=log-transformed number, was as follows:

Y = mud carbonate depth habitat year NvS CvO.

where NvS and CvO are the two contrasts of the three zones. Each term in the model accounts for a single degree of freedom (7 in total). The comparable ANOVA model (Zone-by-Stratum with year as an additive term) would have required 16 degrees of freedom. For prawn species, there were two extra terms (rugosity and moon), increasing to 9 the degrees of freedom for the model.

The covariates were chosen both to reduce residual (unexplained) variation or "noise" and to render the comparison between the closed and open zones as unbiased as possible, given that there will be differences in covariates across the zones. The sediment covariates were chosen as they corresponded with cross-shelf variation (see Chapter 2), the year effect was chosen to remove temporal variation and the depth and habitat covariates were chosen mainly to remove local variation.

Distributional statistics were calculated for the values of the environmental covariates associated with each biological data set. These are similar across data sets but there are some differences because not all sites were visited by all three vessels, and average depth data was reported for the prawn trawler whereas depth at the start of the trawl was used for the fish trawler and the benthic dredge. Correlation coefficients between pairs of environmental covariates were calculated, along with correlations between these and the north–vs–south and closed–vs–open contrasts.

All environmental covariates were then range-standardised, with the minimum value being represented as 0 and the maximum value as 1. This range-standardisation makes it easy to identify which covariates are associated with the greatest range in biomass or abundance of a given animal in the study area: the coefficient for a given covariate shows the range (on the $\log_{10}$ scale) of the predicted weight or number of the animal from the station with the lowest value of that covariate to the station with the highest value.

For the single-species analysis of covariance we have tabulated the following results for the weight and number data for each data set: the significance level for each covariate and the estimated coefficient for each covariate. These two statistics were chosen for their importance in displaying which factors had the strongest influence on the distribution of each species. In order to save space, particularly in the tables of results for the numerous species analysed, we have not tabulated the standard error for each coefficient. This can be derived from the significance level and estimated coefficient, as described below. From a table of two-tail probabilities of the normal distribution, find the standard normal deviate corresponding to the significance level for that covariate. For example, if the significance level is 0.001, the standard normal deviate is 3.291. Divide the (absolute) value of the estimate by this number and the result is the standard error. For example, if the estimate is 1.000 (or −1.000) then the standard error is 0.304. Strictly, the value of the deviate should be obtained from the t-distribution with appropriate degrees of freedom, but this is not necessary because the residual degrees of freedom are in excess of 100.

3.3 RESULTS

3.3.1 Prawn Communities

Distribution of covariates for prawn species data

Table 3.06 shows sample statistics for the environmental covariates relevant to the prawn data (126 tows). Samples covered a wide range of sediment types, with mud ranging from 5.9 percent to 63.8 percent and calcium carbonate covering the complete range from 0 to 100 percent, with half of the stations having more than 87.6 percent calcium carbonate. Depth ranged from 6 m to 43 m, in a relatively symmetric distribution. None of the selected species of structural benthos were present in more than a quarter of the stations, and the maximum amount obtained was about 6.3 kgs (index of 3.80). The rugosity ranged from 0.16 m to 3.06 m, with a median of 0.81 m.

Table 3.06 Distributional statistics for unstandardised environmental covariates used for analysis of prawn data.

Statistic	mud	carbonate	depth	habitat	Rugosity
Minimum	5.9	0.0	6	0.00	0.16
25th percentile	19.2	64.8	22	0.00	0.44
Median	31.1	87.6	28	1.57	0.81
75th percentile	40.8	98.6	32	2.66	1.17
Maximum	63.8	100.0	43	3.80	3.06

There were statistically significant correlations among some of the covariates (Table 3.07). The negative correlation between mud and calcium carbonate reflects the shift from fine sediments of terrigenous origin inshore to coarser sediments of biogenous origin offshore. There are positive correlations between carbonate and depth ($p < 0.001$), carbonate and rugosity ($p < 0.001$), and depth and rugosity ($p < 0.001$), and a negative correlation between mud and rugosity ($p < 0.001$). This pattern of correlations is due to shallow water and a relatively level sea bottom inshore compared with deeper water and a more rugged profile of the sea bottom in the mid-shelf inter-reef area. Mud and year (p = 0.003), and carbonate and year ($p = 0.015$), are correlated because the prawn trawl samples were more completely distributed across the study area in the 1993 survey than the 1992 survey.

When comparing the communities in the open and closed zones, it would be desirable to have no correlations among the environmental covariates. However, such a situation is rarely found in survey data. Given the presence of statistically significant correlations, the difference in biomass or abundance of species between the zones was assessed after taking account of the relationship between the response variables and the environmental covariates. Use of Type II sums-of-squares also meant the explanatory power of each environmental covariate was assessed after allowing for all other terms in the model. It is of more concern when there are significant correlations among the environmental covariates and the open–closed contrast (or the north–south contrast). Only rugosity is significantly correlated with the open–vs–closed contrast ($p = 0.039$) and carbonate is significantly correlated with the north–vs–south contrast ($p = 0.041$), and both correlation coefficients are below 0.2. This suggests that the environmental covariates have a similar distribution in the two open zones and the closed zone. Therefore any significant difference in biomass or abundance between zones could not simply be due to differences in the environment as expressed by the covariates used in this model.

Table 3.07 Correlation coefficient (with significance level where $p \leq 0.05$) between pairs of unstandardised environmental covariates and the contrasts between north and south zones, and open and closed zones – for prawn analysis.

	mud	**carbonate**	**depth**	**habitat**	**rugosity**	**moon**	**year**	**north vs south**	**closed vs open**
mud	1.000	–0.220 (0.012)	–0.063	–0.095	–0.520 (<0.001)	0.182 (0.044)	–0.264 (0.003)	–0.169	0.131
carbonate		1.000	0.453 (<0.001)	0.084	0.299 (<0.001)	0.013	0.217 (0.015)	0.183 (0.041)	0.046
depth			1.000	–0.032	0.376 (<0.001)	0.019	0.107	0.074	–0.065
habitat				1.000	–0.125	–0.036	0.054	–0.016	–0.009
rugosity					1.000	–0.097	0.101	0.044	–0.184 (0.039)
moon						1.000	–0.230 (0.010)	0.168	0.129
year							1.000	–0.093	0.007

Prawn species with a significant difference between zones closed and open to trawling

Table 3.08 shows the significance level for all environmental covariates and the closed–open difference, for log-transformed weight. Table 3.09 shows the corresponding estimate of the covariate coefficients. Tables 3.10 and 3.11 give the significance level and estimated coefficients for log-transformed number.

General patterns were similar in both the prawn biomass and abundance data. Five species showed a significant difference in biomass ($p \leq 0.05$) between the closed and open zones: *Metapenaeopsis lamellata* and *Metapenaeopsis mogiensis* ("coral" prawns); *Metapenaeus endeavouri* (the commercially important "true endeavour" prawn), *Penaeus esculentus* (the commercially important "tiger" prawn) and *Penaeus longistylus* (the commercially important "red-spot king" prawn).

The coral prawns were more abundant in the closed zone (positive coefficient) while the other three, commercial, prawns were more abundant in the open zone (negative coefficient). These species also showed significant relationships with the sediment covariates: the coefficient for mud was negative for the coral prawns (associated with reef-shoals) but positive for *Metapenaeus endeavouri* and *Penaeus esculentus* (concentrated in the inshore lagoon). This pattern was also reflected in the carbonate covariate for all of these species: positive for the two coral prawns, negative for *Metapenaeus endeavouri* and *Penaeus esculentus.* The sediment coefficients for *Penaeus longistylus* were as expected for a species that is associated with the reef-shoal stratum but were not statistically significant. Its large, positive coefficient for depth was, however, consistent with the generally deeper offshore sites.

Trends in the significance of each environmental covariate showed a complex pattern across the 14 species. The habitat covariate, as measured in this study, was not significant for any prawn species. The three-dimensional complexity or rugosity of the sampling sites was significant in only two species, *Metapenaeopsis crassissima* and *Penaeus esculentus.* The coefficient was negative in the latter case, indicating that *Penaeus esculentus* occurred over flat rather than complex sea bottom. Lunar cycle was significant for the lagoon-associated species *Metapenaeus endeavouri*, *Penaeus esculentus* and *Penaeus latisulcatus.* For all significant species, it was positive, indicating a higher catch in the three weeks when the moon is not at its fullest. Depth was significant for both king prawn species (*Penaeus longistylus* and *Penaeus latisulcatus*) although the coefficients were positive and negative (deep and shallow) respectively. Depth was also significant for *Penaeus semisulcatus*, but this is a relatively rare species in northern Australia with a narrow distribution.

Table 3.08 Significance level for terms in analysis of covariance model fitted to log-transformed weight for prawn species.

Species	***f***	**mud**	**carbonate**	**depth**	**habitat**	**rugosity**	**moon**	**year**	**north Vs South**	**closed vs open**
Metapenaeopsis crassissima	6	.030	.337	.365	.589	.047	.054	.181	.384	.107
Metapenaeopsis lamellata	22	<.001	.020	.398	.339	.803	.834	.651	.332	.010
Metapenaeopsis mogiensis	31	<.001	.001	.891	.087	.538	.545	.032	.796	.044
Metapenaeopsis palmensis	53	.930	.425	.163	.745	.141	.026	.005	.017	.065
Metapenaeopsis rosea	64	.001	.783	.139	.276	.295	.169	.812	.010	.231
Metapenaeopsis wellsi	6	.080	.520	.499	.115	.238	.011	.168	.921	.627
Metapenaeus endeavouri	96	<.001	.001	.111	.468	.124	<.001	.062	.489	<.001
Penaeus esculentus	89	<.001	.035	.239	.245	.011	.030	.036	.079	.014
Penaeus latisulcatus	56	.090	<.001	.003	.098	.120	.004	.819	.267	.264
Penaeus longistylus	99	.413	.585	.012	.343	.282	.156	.167	.005	.010
Penaeus semisulcatus	13	.198	.425	.001	.774	.404	.275	.868	.052	.978
Trachypenaeus anchoralis	26	.861	.030	.867	.452	.157	.331	.068	.482	.145
Trachypenaeus curvirostris	25	<.001	.049	.033	.051	.638	.362	.018	.567	.533
Trachypenaeus granulosus	58	.798	.257	.002	.520	.104	.001	.010	.013	.090

Table 3.09 Estimated coefficient for terms in analysis of covariance model fitted to log-transformed weight for prawn species.

Species	**mud**	**carbonate**	**depth**	**habitat**	**rugosity**	**moon**	**year**	**north vs south**	**closed vs open**
Metapenaeopsis crassissima	–0.290	0.132	0.129	–0.040	–0.103	0.104	0.074	0.036	–0.086
Metapenaeopsis lamellata	–1.338	0.533	0.198	–0.115	–0.021	–0.018	0.041	–0.066	0.230
Metapenaeopsis mogiensis	–2.261	1.084	0.044	–0.283	–0.072	–0.073	0.269	–0.024	0.244
Metapenaeopsis palmensis	0.035	–0.331	0.602	–0.072	–0.231	0.364	–0.476	0.302	–0.298
Metapenaeopsis rosea	–1.876	0.154	0.863	–0.325	–0.221	0.301	–0.054	0.445	–0.261
Metapenaeopsis wellsi	–0.222	0.084	–0.092	0.110	0.058	0.132	0.073	0.004	0.025
Metapenaeus endeavouri	1.892	–0.994	0.463	–0.108	–0.162	0.558	0.211	0.058	–0.393
Penaeus esculentus	1.939	–0.453	–0.261	0.132	–0.207	0.182	0.181	–0.114	–0.205
Penaeus latisulcatus	–0.582	–2.068	–1.104	–0.314	–0.208	0.403	0.033	–0.119	0.154
Penaeus longistylus	–0.353	0.244	1.174	–0.226	–0.181	0.247	0.249	0.388	–0.452
Penaeus semisulcatus	0.119	–0.076	–0.347	–0.015	0.030	–0.041	–0.006	–0.057	0.001
Trachypenaeus anchoralis	0.047	–0.607	0.048	0.111	–0.148	0.105	–0.205	0.059	–0.157
Trachypenaeus curvirostris	–2.149	0.756	0.846	–0.399	–0.067	0.135	0.367	0.066	0.092
Trachypenaeus granulosus	0.115	–0.531	1.522	–0.160	–0.287	0.636	–0.492	0.355	–0.309

Table 3.10 Significance level for terms in analysis of covariance model fitted to log-transformed number for prawn species.

Species	*f*	mud	carbonate	depth	habitat	rugosity	moon	year	north vs south	closed vs open
Metapenaeopsis crassissima	6	.029	.401	.279	.536	.049	.073	.205	.376	.113
Metapenaeopsis lamellata	22	<.001	.025	.292	.599	.662	.489	.835	.367	.009
Metapenaeopsis mogiensis	31	<.001	.001	.780	.133	.335	.764	.035	.707	.033
Metapenaeopsis palmensis	53	.549	.870	.182	.541	.138	.013	.002	.045	.030
Metapenaeopsis rosea	64	.001	.631	.195	.248	.286	.121	.820	.013	.209
Metapenaeopsis wellsi	6	.083	.531	.534	.133	.246	.011	.164	.863	.710
Metapenaeus endeavouri	96	<.001	<.001	.285	.540	.094	<.001	.125	.400	.001
Penaeus esculentus	89	<.001	.003	.050	.293	.016	.053	.070	.126	.038
Penaeus latisulcatus	56	.067	<.001	<.001	.098	.235	.011	.532	.308	.224
Penaeus longistylus	99	.293	.584	.034	.196	.281	.059	.063	.014	.007
Penaeus semisulcatus	13	.279	.338	.001	.816	.595	.264	.895	.082	.818
Trachypenaeus anchoralis	26	.646	.038	.979	.610	.211	.148	.090	.563	.073
Trachypenaeus curvirostris	25	<.001	.069	.017	.037	.625	.425	.018	.492	.463
Trachypenaeus granulosus	58	.717	.305	.002	.579	.075	<.001	.004	.015	.060

Table 3.11 Estimated coefficient for terms in analysis of covariance model fitted to log-transformed number for prawn species.

Species	mud	carbonate	depth	habitat	rugosity	moon	year	north vs south	closed vs open
Metapenaeopsis crassissima	–0.234	0.093	0.124	–0.036	–0.082	0.077	0.056	0.030	–0.068
Metapenaeopsis lamellata	–0.818	0.312	0.151	–0.039	–0.023	–0.037	0.012	–0.038	0.142
Metapenaeopsis mogiensis	–1.770	0.867	0.072	–0.199	–0.090	–0.029	0.213	–0.028	0.207
Metapenaeopsis palmensis	0.185	–0.052	0.445	–0.104	–0.179	0.315	–0.399	0.196	–0.272
Metapenaeopsis rosea	–1.387	0.210	0.590	–0.270	–0.176	0.266	–0.040	0.334	–0.214
Metapenaeopsis wellsi	–0.180	0.067	–0.069	0.086	0.047	0.108	0.060	0.006	0.015
Metapenaeus endeavouri	1.630	–1.129	0.290	–0.085	–0.165	0.459	0.162	0.067	–0.340
Penaeus esculentus	1.980	–0.697	–0.477	0.131	–0.213	0.177	0.171	–0.108	–0.189
Penaeus latisulcatus	–0.427	–1.539	–0.906	–0.213	–0.108	0.240	0.060	–0.074	0.114
Penaeus longistylus	–0.331	0.179	0.725	–0.225	–0.132	0.241	0.246	0.246	–0.344
Penaeus semisulcatus	0.105	–0.096	–0.351	–0.012	0.020	–0.044	–0.005	–0.053	0.009
Trachypenaeus anchoralis	0.095	–0.451	0.006	0.058	–0.101	0.122	–0.148	0.038	–0.150
Trachypenaeus curvirostris	–1.632	0.536	0.737	–0.329	–0.054	0.091	0.284	0.061	0.084
Trachypenaeus granulosus	0.139	–0.409	1.289	–0.118	–0.268	0.555	–0.468	0.298	–0.293

Assessment of the prawn community

For each covariate, we tabulated the number of species that had a significant result, for log-transformed weight and log-transformed number (Table 3.12 and 3.13). The results were tabulated for all species found in at least 6 stations (the '> 5' group) and two subsets of these: the '> 40' group and the '6–40' group.

For most environmental covariates, a third to half of the species had a significant result. Exceptions were: rugosity (2 species, for weight and number) and habitat (none for weight, 1 for number). The closed zone differed statistically from the open zone in one-third of the species.

Table 3.12 Number of prawn species with a significant result ($p \leq 0.05$), for each term in the analysis of covariance model, for log-transformed weight.

Frequency group	Number of species in group	Term in analysis of covariance model								
		mud	carbonate	depth	habitat	rugosity	moon	year	north vs south	closed vs open
> 40	7	3	3	3	0	1	5	3	4	3
6–40	7	4	4	2	0	1	1	2	0	2
> 5	14	7	7	5	0	2	6	5	4	5

Table 3.13 Number of prawn species with a significant result ($p \leq 0.05$), for each term in the analysis of covariance model, for log-transformed number.

Frequency group	Number of species in group	Term in analysis of covariance model								
		mud	carbonate	depth	habitat	rugosity	moon	year	north vs south	closed vs open
> 40	7	3	3	3	0	1	4	2	4	4
6–40	7	4	3	2	1	1	1	2	0	2
> 5	14	7	6	5	1	2	5	4	4	6

The results of multivariate analysis of covariance are shown in Table 3.14 (log-transformed weight) and Table 3.15 (log-transformed number). Only 14 prawn species were found in at least 6 stations, so we were able to analyse the full set. We also analysed two subsets of the prawn species: those found in more than 40 stations (the '> 40' group) and those found in up to 40 stations.

In all groups, the sediment variables (mud and carbonate) were highly statistically significant and were clearly effective in removing 'noise' from the data. Depth was highly significant for all groups and it was clearly a worthwhile covariate to have included. The habitat index was ineffective, except possibly for the '6–40' group where the probability was 0.108 for log-transformed weight and 0.135 for log-transformed number. Rugosity proved to be a better 'habitat' index, particularly for the comprehensive suite of species. Lunar phase was highly significant for the '> 40' group and the comprehensive group. There was a clear difference between the years for the '> 40' group, but only a borderline significant difference for the less common species ('6–40' group).

The difference between the northern and southern sections of the open zone was significant for the '> 40' group. For the less common species, the difference was not significant. For the comprehensive group the probability was borderline significant for log-transformed weight, but no for log-transformed number.

The difference between the closed and open zones was stronger for log-transformed number than for log-transformed weight: for most groups, the significance level was smaller for the number data. The difference between the two zones was highly significant for the '> 40' group and the comprehensive group and significant for log-transformed number for the '6–40' group.

Table 3.14 Significance level for Wilks' lambda in multivariate analysis of covariance of log-transformed weight for prawn species.

Frequency group	**Number of species in group**	**Term in analysis of covariance model**								
		mud	**carbonate**	**depth**	**habitat**	**rugosity**	**moon**	**year**	**north vs south**	**closed vs open**
> 40	7	<.0001	<.0001	.0009	.5711	.1024	<.0001	<.0001	.0255	.0040
6–40	7	<.0001	.0061	.0022	.1080	.0736	.0172	.1489	.4667	.0676
> 5	14	<.0001	<.0001	.0003	.2260	.0128	<.0001	.0005	.1056	.0015

Table 3.15 Significance level for Wilks' lambda in multivariate analysis of covariance of log-transformed number for prawn species.

Frequency group	**Number of species in group**	**Term in analysis of covariance model**								
		mud	**carbonate**	**depth**	**habitat**	**rugosity**	**moon**	**year**	**north vs south**	**closed vs open**
> 40	7	<.0001	<.0001	<.0001	.4986	.1849	.0016	<.0001	.0959	.0039
6–40	7	<.0001	.0050	.0012	.1349	.0662	.0313	.1579	.5412	.0260
> 5	14	<.0001	<.0001	<.0001	.2605	.0149	.0005	.0016	.2160	.0005

3.3.2 Bycatch communities

Distribution of covariates for bycatch data

Table 3.16 shows sample statistics for the environmental covariates relevant to the bycatch data (122 tows). Samples covered a wide range of sediment types, with mud ranging from 5.9 percent to 63.8 percent and calcium carbonate covering the complete range from 0 to 100 percent, with half of the stations having more than 87.5 percent calcium carbonate. Depth ranged from 6 m to 43 m, in a relatively symmetric distribution. None of the selected species of structural benthos were present in more than a quarter of the stations, and the maximum amount obtained was about 6.3 kgs (index of 3.80).

Table 3.16 Distributional statistics for unstandardised environmental covariates used for analysis of bycatch data.

Statistic	mud	carbonate	depth	habitat
Minimum	5.9	0.0	8	0.00
25th percentile	21.1	64.7	22	0.00
Median	31.1	87.5	28	1.55
75th percentile	40.8	98.5	32	2.70
Maximum	63.8	100.0	43	3.80

The correlation coefficients for environmental covariates in the bycatch data (Table 3.17) are more or less the same as for the prawn species data. They would have been identical (with the exception of the covariates for lunar phase and sea-bottom rugosity) if no tows had been rejected for the bycatch data set. Mud and carbonate are negatively correlated ($p = 0.013$) because of the shift from fine sediments of terrigenous origin inshore to coarser sediments of biogenic origin in the mid-shelf inter-reef.area. Carbonate and depth are positively correlated ($p < 0.001$) because deeper water was mostly found in the mid-shelf inter-reef area. The significant correlations between mud and year ($p = 0.004$), and between carbonate and year ($p = 0.024$), are a consequence of samples being more completely distributed through the study area in the 1993 survey than the 1992 survey. For the bycatch data, no covariates were significantly correlated with the open–vs–closed contrast. Two covariates (mud and carbonate) were significantly correlated with the north–vs–south contrast ($p = 0.031$ and $p = 0.041$ respectively).

Table 3.17 Correlation coefficient (with significance level where $p \leq 0.05$) between pairs of unstandardised environmental covariates and the contrasts between north and south zones, and open and closed zones — for bycatch analysis

	mud	carbonate	depth	habitat	year	north vs south	closed vs open
Mud	1.000	–0.225 (0.013)	–0.076	–0.110	–0.261 (0.004)	–0.195 (0.031)	0.126
carbonate		1.000	0.463 (<0.001)	0.075	0.205 (0.024)	0.186 (0.041)	0.040
depth			1.000	–0.066	0.116	0.042	–0.109
habitat				1.000	0.051	–0.037	–0.020
year					1.000	–0.092	0.010

Bycatch species with a significant difference between zones closed and open to trawling

Of the 117 species or groups of bycatch analysed, we selected for closer examination the subset of 14 species that had a statistically significant difference between the closed and open zones either for log-transformed weight or for log-transformed number (usually both were significant). Table 3.18 shows, for all environmental covariates and the closed–open difference, the significance level for log-transformed weight. Table 3.19 shows the corresponding estimate of the covariate coefficients. Tables 3.20 and 3.21 give the significance level and estimated coefficients for log-transformed number.

There were 14 species with a statistically significant ($p \leq 0.05$) difference between the closed zone and the open zone; 8 were more abundant in the closed zone, 6 more abundant in the open zone.

The three species with the highest difference of abundance (on the $\log_{10}$ scale) in favour of the closed zone were: Porifera (0.932 for weight; 0.214 for number), *Upeneus tragula* (0.345/0.310), and *Lethrinus genivittatus* (0.363/0.363). Porifera represents all species of sponge. These were differentiated into species only for the benthic dredge. Nonetheless it is interesting that there appears to be a ratio of about 8 to 1 in favour of the closed zone for biomass of the type of Porifera caught by prawn trawlers. The ratio for number of sponges is 1.6 to 1. The larger ratio for weight than number suggests that there were larger specimens of the species caught by trawlers in the closed zone than in the open zone. This is the largest difference between the open and closed zones for any species or class in any of the four data sets.

The sponges were more abundant in inshore, shallow waters: the coefficients for mud, carbonate and depth are very large (carbonate and depth are significant). There was a greater biomass of sponge (Porifera) per station in the northern part of the open zone, but the number of sponges differed very little between the northern and southern parts of the open zone.

The three species with the highest difference of abundance in favour of the open zone were: *Saurida undosquamis* (–0.312/–0.217), *Portunus rubromarginatus* (–0.268/–0.285), and *Synodus hoshinonis* (–0.254/–0.188). For *Saurida undosquamis*, back-transformation of the difference yields a ratio of twice as much biomass per station in the open zone as in the closed zone.

Saurida undosquamis was a common species (112 stations out of 122), but appeared to be more abundant inshore (significant, large positive coefficient for mud). There was a significant difference in its abundance between years. *Portunus rubromarginatus* was common (109 stations) and showed no relationship with any of the environmental covariates included in the model. *Synodus hoshinonis* (22 stations) also showed no relationship with environmental covariates, except perhaps with carbonate ($p < 0.1$).

Table 3.18 Significance level for log-transformed weight for bycatch species/taxa with a significant ($p \leq 0.05$) difference between closed and open zones.

Species	***f***	**mud**	**carbonate**	**depth**	**habitat**	**year**	**north vs south**	**closed vs open**
Apogon poecilopterus	23	.013	.009	.167	.766	< .001	< .001	.017
Engyprosopon grandisquama	87	.014	.001	.951	.761	.164	< .001	.060
Gerres oyena	32	.256	.049	.010	.521	.265	.596	.026
Leiognathus sp.	49	< .001	.594	.111	.120	.065	.421	.057
Lethrinus genivittatus	111	.234	.376	.018	.350	.114	< .001	.009
Rhynchostracion nasus	73	< .001	.025	.322	.099	.717	.795	.441
Saurida undosquamis	112	.003	.258	.183	.225	.037	.864	.004
Sorsogona tuberculata	90	.007	.006	.172	.649	.037	.080	.161
Synodus hoshinonis	22	.659	.087	.259	.780	.756	.022	.005
Upeneus luzonius	56	.027	.255	.001	.631	.146	.097	.027
Upeneus tragula	90	< .001	.013	.861	.050	.221	< .001	.016
Porifera (mixed species)	51	.272	.045	.020	.617	.104	.012	.002
Hydrozoa	15	.029	.117	.008	.131	< .001	.752	.006
Portunus rubromarginatus	109	.126	.732	.485	.207	.546	.163	.034

Table 3.19 Estimated coefficient for log-transformed weight for bycatch species/taxa with a significant ($p \leq 0.05$) difference between closed and open zones.

Species	**mud**	**carbonate**	**depth**	**habitat**	**year**	**north vs south**	**closed vs open**
Apogon poecilopterus	0.471	–0.607	–0.315	0.036	0.395	–0.304	–0.214
Engyprosopon grandisquama	0.604	–1.013	0.018	–0.047	0.164	0.524	–0.217
Gerres oyena	0.190	–0.405	–0.528	–0.068	–0.090	0.032	0.177
Leiognathus sp.	1.265	–0.227	–0.678	0.348	–0.312	0.163	0.314
Lethrinus genivittatus	0.346	0.314	–0.842	0.173	–0.221	0.428	0.363
Rhynchostracion nasus	2.084	–0.976	0.423	0.372	–0.061	–0.034	0.127
Saurida undosquamis	0.693	0.318	–0.372	–0.178	0.232	0.014	–0.312
Sorsogona tuberculata	1.044	1.312	0.638	0.111	–0.389	0.248	–0.253
Synodus hoshinonis	–0.083	0.396	0.258	–0.034	0.028	0.160	–0.254
Upeneus luzonius	–0.466	–0.290	–0.832	0.064	0.146	0.127	0.219
Upeneus tragula	1.710	–0.926	0.064	0.381	–0.178	0.421	0.345
Porifera (mixed species)	0.678	–1.523	–1.764	0.197	0.484	0.572	0.932
Hydrozoa	–0.415	–0.362	–0.613	0.182	–0.468	0.022	0.249
Portunus rubromarginatus	0.410	–0.112	–0.227	–0.216	0.078	0.137	–0.268

Table 3.20 Significance level for log-transformed number for bycatch species/taxa of interest with a significant ($p \leq 0.05$) difference between closed and open zones.

Species	*f*	mud	carbonate	depth	habitat	year	north vs south	closed vs open
Apogon poecilopterus	23	.024	.005	.099	.827	< .001	< .001	.007
Engyprosopon grandisquama	87	.047	.001	.719	.713	.129	< .001	.020
Gerres oyena	32	.477	.036	.001	.319	.273	.617	.009
Leiognathus sp.	49	.005	.374	.022	.157	.171	.729	.017
Lethrinus genivittatus	111	.274	.562	.003	.494	.352	< .001	.004
Rhynchostracion nasus	73	< .001	.002	.727	.318	.166	.622	.034
Saurida undosquamis	112	< .001	.713	.163	.379	.006	.214	.003
Sorsogona tuberculata	90	.128	.002	.283	.935	.057	.043	.047
Synodus hoshinonis	22	.529	.087	.236	.776	.734	.019	.003
Upeneus luzonius	56	.054	.225	< .001	.658	.040	.064	.020
Upeneus tragula	90	< .001	.005	.668	.047	.197	< .001	.008
Porifera (mixed species)	51	.449	.230	.059	.327	.105	.125	.002
Hydrozoa	15	.041	.284	.052	.496	< .001	.488	.044
Portunus rubromarginatus	109	.124	.479	.691	.181	.291	.272	.015

Table 3.21 Estimated coefficient for log-transformed number for bycatch species/taxa with a significant ($p \leq 0.05$) difference between closed and open zones.

Species	mud	carbonate	depth	habitat	year	north vs south	closed vs open
Apogon poecilopterus	0.274	–0.420	–0.242	0.017	0.241	–0.202	–0.155
Engyprosopon grandisquama	0.395	–0.826	–0.086	–0.046	0.145	0.421	–0.217
Gerres oyena	0.102	–0.374	–0.578	–0.092	–0.076	0.026	0.178
Leiognathus sp.	0.645	–0.245	–0.633	0.204	–0.148	0.028	0.254
Lethrinus genivittatus	0.291	0.188	–0.964	0.116	–0.119	0.471	0.363
Rhynchostracion nasus	0.987	–0.756	–0.085	0.127	–0.134	0.036	0.200
Saurida undosquamis	0.635	0.078	–0.295	–0.098	0.235	–0.079	–0.250
Sorsogona tuberculata	0.310	0.771	0.265	0.011	–0.187	0.152	–0.191
Synodus hoshinonis	–0.085	0.283	0.194	–0.024	0.022	0.117	–0.188
Upeneus luzonius	–0.371	–0.285	–0.914	0.054	0.191	0.131	0.211
Upeneus tragula	1.236	–0.860	–0.129	0.317	–0.154	0.381	0.310
Porifera (mixed species)	0.108	–0.209	–0.329	0.089	0.111	0.080	0.214
Hydrozoa	–0.128	–0.082	–0.148	0.027	–0.160	0.016	0.059
Portunus rubromarginatus	0.380	–0.213	–0.119	–0.211	0.125	0.099	–0.285

Assessment of the bycatch community

For each covariate, we tabulated the percentage of species that had a significant result, for log-transformed weight and log-transformed number. (Table 3.22 and 3.23). The percentage was tabulated for three frequency groups and for the full set of species that was analysed.

Mud was the best predictor in terms of the percentage of species for which this covariate was significant: 56% for weight (54% for number) overall; ranging from 28% (31%) for the '11–20' group to 79% (70%) for the '> 40' group. Carbonate, depth and the north–south difference were clearly important, though they had less explanatory power than mud. Carbonate was significant for 26% (28%), depth for 26% (33%) and north–south for 32% (33%) of species. For carbonate, significant results were found more often in commoner species than in rarer species. For depth, there were more significant results for the '21–40' group. The year effect showed no particular trend: 28% (34%) overall. The habitat index was apparently a poor predictor of the distribution for species: it was significant for 7% (6%) of all species analysed. The closed zone differed statistically from the open zone in only 9% (12%) of the species analysed, with a trend from a low rate of 3% (3%) in the '11–20' group to a rate of 14% (23%) in the '> 40' group.

Table 3.22 Percentage of bycatch species with a significant result ($p \leq 0.05$), for each term in the analysis of covariance model, for log-transformed weight.

Frequency group	Number of species in group	Term in analysis of covariance model						
		mud (%)	carbonate (%)	depth (%)	habitat (%)	year (%)	north vs south (%)	closed vs open (%)
> 40	44	79	75	25	5	27	39	14
21–40	41	53	27	27	7	24	27	7
11–20	32	28	19	25	9	34	28	3
> 10	117	56	26	26	7	28	32	9

Table 3.23 Percentage of bycatch species with a significant result ($p \leq 0.05$), for each term in the analysis of covariance model, for log-transformed number.

Frequency group	Number of species in group	Term in analysis of covariance model						
		mud (%)	carbonate (%)	depth (%)	habitat (%)	year (%)	north vs south (%)	closed vs open (%)
> 40	44	70	34	30	5	36	43	23
21–40	41	54	29	39	5	30	27	7
11–20	32	31	19	31	9	34	28	3
> 10	117	54	28	33	6	34	33	12

Full details of the significance level and the estimated coefficient for all covariates and the difference between zones are given in Appendices 3.B.

The results of multivariate analysis of covariance are shown in Table 3.24 (log-transformed weight) and Table 3.25 (log-transformed number). In all groups of commoner species ('>40', '21–40' and '11–20'), the sediment variables (mud and carbonate) were highly statistically significant and were clearly effective in removing 'noise' from the data. This was also the case when the largest possible group was analysed (the '> 14' group). For the rarer groups (3–10 stations), mud was statistically significant while carbonate was not. Depth was highly significant for the groups containing commoner species (present in at least 11 stations), and for rarer species it was probably a worthwhile covariate to have included. The habitat index was almost completely ineffective, except for the large ('> 14') group where the probability for log-transformed number was highly significant, although that for log-transformed weight was not. There was a clear difference between the years for the groups consisting of the commoner species, but no clear difference for the rarer species.

The difference between the northern and southern sections of the open zone was highly significant for the three groups comprising the commoner species ('> 40', '21–40' and '11–20' groups). For the rare species, the difference was not significant. For the '> 14' group the north–south difference was highly significant.

The difference between the closed and open zones was significant for common groups ('>40' and '21–40') and highly significant for log-transformed number (also significant for log-transformed weight) in the most comprehensive group ('> 14').

Table 3.24 Significance level for Wilks' lambda in multivariate analysis of covariance of log-transformed weight for bycatch species.

Frequency group	Number of species in group	Term in analysis of covariance model						
		mud	carbonate	depth	habitat	year	north vs south	closed vs open
> 40	44	<.0001	.0003	.0006	.7982	<.0001	<.0001	.0356
21–40	41	<.0001	<.0001	.0003	.6140	<.0001	<.0001	.0192
11–20	32	.0003	.0023	<.0001	.1744	<.0001	<.0001	.2445
6–10	42	.0064	.1150	.0025	.2355	.1695	.6965	.3234
3–5	44	.0553	.3650	.0117	.7904	.1147	.1256	.7512
> 14	97	.0017	.0031	.0171	.5838	.0003	<.0001	.0168

Table 3.25 Significance level for Wilks' lambda in multivariate analysis of covariance of log-transformed number for bycatch species.

Frequency group	Number of species in group	Term in analysis of covariance model						
		mud	carbonate	depth	habitat	year	north vs south	closed vs open
> 40	44	<.0001	<.0001	<.0001	.5197	<.0001	<.0001	.0133
21–40	41	<.0001	<.0001	<.0001	.5406	<.0001	<.0001	.0194
11–20	32	.0011	.0014	<.0001	.2279	<.0001	.0002	.4707
6–10	42	.0020	.0817	.0025	.2086	.1188	.3974	.2194
3–5	44	.0173	.2974	.0096	.8579	.0723	.0655	.6948
> 14	97	.0029	.0136	.0131	.0317	<.0001	<.0001	.0005

3.3.3 Fish trawl communities

Distribution of covariates for fish trawl data

Table 3.26 shows sample statistics for the environmental covariates relevant to the fish trawl data (149 tows). Samples covered a wide range of sediment types, with mud ranging from 3.4 percent to 70.7 percent and calcium carbonate covering the complete range from 0 to 100 percent, with half of the stations having more than 89.7 percent calcium carbonate. Depth ranged from 6 m to 60 m, in a relatively symmetric distribution. None of the selected species of structural benthos were present in more than a quarter of the stations, and the maximum amount obtained was about 40 kgs (index of 4.61).

Table 3.26 Distributional statistics for unstandardised environmental covariates used for analysis of fish trawl data

Statistic	mud	carbonate	depth	habitat
Minimum	3.4	0.0	6.0	0.00
25th percentile	12.3	71.9	23.0	0.00
Median	29.0	89.7	28.0	1.84
75th percentile	40.2	98.7	32.0	2.80
Maximum	70.7	100.0	60.0	4.61

Mud was negatively correlated with carbonate ($p < 0.001$) for fish trawl data (Table 3.27), and carbonate is positively correlated with depth ($p < 0.001$). These reflect the trend from fine, terrigenous sediments and shallower water inshore to coarser, biogenic sediments and deeper water in the mid-shelf inter-reef area, and are consistent with the patterns for the prawn species data (Table 3.07) and the bycatch data (Table 3.17). For the fish trawl data, there are no statistically significant correlations between the environmental covariates and either the closed–vs–open contrast or the north–vs–south contrast. This may have been due in part to the relatively more complete distribution of samples throughout the study area in both surveys.

Table 3.27 Correlation coefficient (with significance level where $p \leq 0.05$) between pairs of unstandardised environmental covariates and the contrasts between north and south zones, and open and closed zones — for fish trawl analysis.

	mud	carbonate	depth	habitat	year	north vs south	closed vs open
mud	1.000	–0.305 (<0.001)	–0.062	–0.120	–0.155	–0.113	0.107
carbonate		1.000	0.368 (<0.001)	0.115	0.078	0.110	0.016
depth			1.000	–0.135	0.029	0.030	–0.128
habitat				1.000	–0.001	–0.088	0.004
year					1.000	–0.155	–0.030

Fish trawl species with a significant difference between zones closed and open to trawling

Of the 82 species of fish selected for analysis, we selected for closer examination the subset of 10 species that had a statistically significant difference between the closed and open zones either for log-transformed weight or for log-transformed number (usually both were significant). Table 3.28 shows the significance level for all environmental covariates and the closed–open difference, for log-transformed weight; Table 3.29 shows the corresponding estimate of the covariate coefficients. Tables 3.30 and 3.31 give the significant level and estimated coefficients for log-transformed number.

There were 10 species with a statistically significant ($p \leq 0.05$) difference between the closed zone and the open zone; 7 were more abundant in the closed zone, 3 more abundant in the open zone.

The three species with the highest difference of abundance (on the $\log_{10}$ scale) in favour of the closed zone were: *Lethrinus genivittatus* (0.443 for weight; 0.442 for number), *Pentaprion longimanus* (0.324/0.330), and *Upeneus asymmetricus* (0.312/0.295). For *Lethrinus genivittatus*, back-transformation of the difference yields a ratio of 2.8 times as much biomass per station in the closed zone as in the open zone.

The distributional properties of these three species are varied. *Lethrinus genivittatus* was ubiquitous (139 out of 149 stations), showing no relationship with sediment but a preference for shallower waters and a fairly large difference in abundance between the two years. It was found in greater quantities in the northern part of the open zone than in the southern part. *Upeneus asymmetricus* was not common (30 stations), but showed no relationship with any of the covariates, suggesting an even distribution throughout the study area. *Pentaprion longimanus* was moderately common (39 stations), with higher abundance at inshore stations (significant positive coefficient for mud).

Three species were more abundant in the open zone were: *Canthigaster compress* (–0.232/–0.220), *Saurida micropectoralis* (–0.152/–0.164), and *Synodus saganeus* (–0.141/–0.113). For *Canthigaster compressa*, back-transformation of the difference yields a ratio of 1.7 times as much biomass per station in the open zone as in the closed zone.

None of these three species was common. *Canthigaster compressa* (25 stations out of 149) was more abundant in the mid-shelf inter-reef (negative coefficient for mud, positive coefficient for carbonate) but appeared to be more abundant in shallow water, which probably the tops of shoals. It was nearly twice as abundant in the south as in the north. *Saurida micropectoralis* (19 stations) appeare to be more abundant inshore, on muddy sediment. It was also more abundant in the south than the north. *Synodus saganeus* (29 stations) appeared to be evenly distributed, as it showed no relationship with any of the covariates.

Table 3.28 Significance level for log-transformed weight for fish species with a significant ($p \leq 0.05$) difference between closed and open zones.

Species	*f*	mud	carbonate	depth	habitat	year	north vs south	Closed vs open
Abalistes stellaris	18	< .001	.243	.141	.775	.081	.657	.001
Canthigaster compressa	25	< .001	.006	.010	.097	.009	< .001	.019
Carangoides hedlandensis	46	< .001	.109	.992	.491	.017	.130	.057
Lethrinus genivittatus	139	.272	.187	.012	.123	.022	.047	.006
Pentaprion longimanus	39	< .001	.249	.085	.191	.322	.104	.003
Saurida micropectoralis	19	.025	.120	.487	.341	.263	< .001	.008
Synodus sageneus	16	.259	.911	.769	.799	.125	.410	.023
Upeneus asymmetricus	30	.902	.333	.869	.496	.692	.947	.007
Upeneus luzonius	44	< .001	.347	.522	.765	.016	.034	.022
Upeneus sulphureus	12	.001	.027	.630	.270	.498	.115	.042

Table 3.29 Estimated coefficient for log-transformed weight for fish species with a significant ($p \leq 0.05$) difference between closed and open zones

Species	mud	carbonate	depth	habitat	year	north vs south	closed vs open
Abalistes stellaris	–0.984	0.266	0.429	0.042	–0.152	–0.029	0.296
Canthigaster compressa	-1.071	0.719	–0.856	0.274	–0.258	–0.313	–0.232
Carangoides hedlandensis	1.065	–0.421	–0.003	–0.115	–0.239	–0.115	0.191
Lethrinus genivittatus	0.367	0.552	-1.346	0.413	–0.366	0.242	0.443
Pentaprion longimanus	1.482	–0.328	0.627	–0.238	–0.107	–0.134	0.324
Saurida micropectoralis	0.267	–0.231	–0.131	–0.090	–0.063	–0.193	–0.152
Synodus sageneus	0.146	–0.018	–0.061	0.026	–0.095	–0.039	–0.141
Upeneus asymmetricus	–0.029	–0.290	–0.063	–0.130	–0.045	0.006	0.312
Upeneus luzonius	-1.072	–0.281	0.244	0.057	–0.276	–0.184	0.263
Upeneus sulphureus	0.333	–0.267	0.074	0.085	0.031	0.055	0.094

Table 3.30 Significance level for log-transformed number for fish species with a significant ($p \leq .05$) difference between closed and open zones.

Species	f	mud	carbonate	depth	habitat	year	north vs south	closed vs open
Abalistes stellaris	18	< .001	.242	.195	.834	.079	.598	.003
Canthigaster compressa	25	< .001	.003	.002	.088	.041	< .001	.005
Carangoides hedlandensis	46	< .001	.173	.578	.337	.023	.166	.048
Lethrinus genivittatus	139	.436	.370	.010	.135	.020	.038	.004
Pentaprion longimanus	39	< .001	.213	.139	.217	.362	.120	.003
Saurida micropectoralis	19	.031	.136	.299	.259	.288	< .001	.008
Synodus sageneus	16	.233	.967	.591	.644	.110	.362	.020
Upeneus asymmetricus	30	.826	.323	.812	.429	.704	.966	.007
Upeneus luzonius	44	< .001	.310	.594	.829	.017	.042	.013
Upeneus sulphureus	12	.001	.019	.673	.257	.521	.122	.040

Table 3.31 Estimated coefficient for log-transformed number for fish species with a significant ($p \leq .05$) difference between closed and open zones

Species	mud	carbonate	depth	habitat	year	north vs south	Closed vs open
Abalistes stellaris	–0.505	0.144	0.203	0.016	–0.082	–0.019	0.140
Canthigaster compressa	–0.795	0.605	–0.802	0.223	–0.159	–0.286	–0.220
Carangoides hedlandensis	0.835	–0.284	–0.147	–0.128	–0.182	–0.083	0.157
Lethrinus genivittatus	0.247	0.357	–1.322	0.382	–0.354	0.240	0.442
Pentaprion longimanus	1.473	–0.363	0.551	–0.230	–0.101	–0.131	0.330
Saurida micropectoralis	0.280	–0.242	–0.214	–0.117	–0.065	–0.204	–0.164
Synodus sageneus	0.122	–0.005	–0.087	0.038	–0.078	–0.034	–0.113
Upeneus asymmetricus	–0.050	–0.280	–0.086	–0.143	–0.041	0.003	0.295
Upeneus luzonius	–1.037	–0.290	0.194	0.039	–0.262	–0.169	0.272
Upeneus sulphureus	0.310	–0.274	0.062	0.084	0.028	0.052	0.092

Assessment of fish community from fish trawl

For each covariate, we tabulated the percentage of species that had a significant result, for log-transformed weight and log-transformed number (Table 3.32 and 3.33). The percentage was tabulated for three frequency groups and for the full set of species that was analysed.

Mud was the best predictor in terms of the percentage of species for which this covariate was significant: 72% for weight (70% for number) overall; ranging from 62% (62%) for the '11–20' group to 88% (84%) for the '> 40' group. Depth, year and the north–south difference were clearly important, though they had less explanatory power than mud. Depth was significant for 17% (15%), year for 23% (27%) and north–south for 21% (20%) of species. The year effect was significant for 9% (12%) for rarer species and went up to 32% (40%) for commoner species. Carbonate was not a strong predictor: significant for 9% (12%) of species. The habitat index was a poor predictor of the distribution for species: it was significant for 4% (4%) of all species analysed. The closed zone differed statistically from the open zone in only 11% (12%) of the species analysed, a rate that was almost constant across frequency groups.

Table 3.32 Percentage of fish species with a significant result ($p \leq 0.05$), for each term in the analysis of covariance model, for log-transformed weight.

Frequency group	Number of species in group	Term in analysis of covariance model						
		Mud (%)	carbonate (%)	depth (%)	habitat (%)	year (%)	north vs south (%)	closed vs open (%)
> 40	25	88	4	20	4	32	24	8
21–40	25	68	8	16	4	32	20	12
11–20	32	62	12	16	3	9	19	13
> 10	82	72	9	17	4	23	21	11

Table 3.33 Percentage of fish species with a significant result ($p \leq 0.05$), for each term in the analysis of covariance model, for log-transformed number.

Frequency group	Number of species in group	Term in analysis of covariance model						
		Mud (%)	carbonate (%)	depth (%)	habitat (%)	year (%)	north vs south (%)	closed vs open (%)
> 40	25	84	8	24	4	40	20	12
21–40	25	64	16	12	8	32	20	12
11–20	32	62	12	9	0	12	19	12
> 10	82	70	12	15	4	27	20	12

Full details of the significance level and the estimated coefficient for all covariates and the difference between zones are given in Appendix 3.C.

The results of multivariate analysis of covariance are shown in Table 3.34 (log-transformed weight) and Table 3.35 (log-transformed number). In all groups except the rarest species (the '3–5' group), the sediment variables (mud and carbonate) were highly statistically significant and were clearly effective in removing 'noise' from the data. This was still the case when the largest possible group was analysed (the '> 14' group). Depth was highly significant for most groups except the '11–20' and '3–5' groups. The habitat index was completely ineffective. There was a clear difference between the years for the groups comprising the commoner species, but no clear difference for the rarer species.

The difference between the northern and southern sections of the open zone was highly significant for the two groups consisting of the commoner species ('> 40' and '21–40' groups) and the '> 14' group. For the uncommon ('11-20') group, the north-south difference was significant.

The difference between the closed and open zones was stronger for log-transformed number than for log-transformed weight: for most groups, the significance level was smaller for the number data. However, the difference between the two zones was barely detectable and must be much smaller than the north–south difference, especially as there is a larger set of samples for comparing closed with open than for comparing north and south sections of the open zone.

Table 3.34 Significance level for Wilks' lambda in multivariate analysis of covariance of log-transformed weight for fish species.

Frequency group	Number of species in group	Term in analysis of covariance model						
		mud	carbonate	depth	habitat	year	north vs south	closed vs open
> 40	25	<.0001	.2067	<.0001	.4428	.0011	<.0001	.1268
21–40	25	<.0001	.0095	.0024	.6657	<.0001	<.0001	.1539
11–20	32	<.0001	.0127	.0150	.2204	.0036	.0069	.0801
6–10	34	.0006	.0142	.0012	.4935	.1973	.0651	.0262
3–5	44	.1161	.0687	.0810	.4104	.1476	.0237	.1268
> 14	69	<.0001	.0042	<.0001	.8440	.0007	<.0001	.0022

Table 3.35 Significance level for Wilks' lambda in multivariate analysis of covariance of log–transformed number for fish species

Frequency group	Number of species in group	Term in analysis of covariance model						
		mud	carbonate	depth	habitat	year	north vs south	closed vs open
> 40	25	<.0001	.1995	.0002	.3065	<.0001	<.0001	.0403
21–40	25	<.0001	.0043	<.0001	.7089	<.0001	<.0001	.0548
11–20	32	<.0001	.0029	.0379	.1840	.0021	.0245	.0357
6–10	34	.0006	.0035	.0021	.5568	.3498	.0553	.0125
3–5	44	.0476	.3651	.1672	.3191	.1927	.1048	.1332
> 14	69	<.0001	.0007	<.0001	.8933	.0002	<.0001	.0072

3.3.4 Benthic dredge invertebrate communities

Distribution of covariates for benthic dredge data

Table 3.36 shows sample statistics for the environmental covariates relevant to the benthic dredge data (157 tows). Samples covered a wide range of sediment types, with mud ranging from 3.4 percent to 70.7 percent and calcium carbonate covering the complete range from 0 to 100 percent, with half of the stations having more than 91.5 percent calcium carbonate. Depth ranged from 6 m to 60 m, in a relatively symmetric distribution. None of the selected species of structural benthos were present in more than a quarter of the stations, and the maximum amount obtained was about 40 kgs (index of 4.61).

Table 3.36 Distributional tatistics for unstandardised environmental covariates used for analysis of dredge data.

Statistic	mud	carbonate	depth	habitat
Minimum	3.4	0.0	6	0.00
25th percentile	12.7	73.6	22	0.00
Median	28.7	91.5	28	1.94
75th percentile	40.6	98.7	32	2.82
Maximum	70.7	100.0	60	4.61

The patterns for the benthic dredge (Table 3.37) are almost identical to those for the fish trawl (Table 3.27), despite some differences in the locations where sampling was successful and a different group of tows being excluded for each device. There was a negative correlation between mud and carbonate ($p < 0.001$), a positive correlation between carbonate and depth ($p < 0.001$) and there are no statistically significant correlations between the environmental covariates and either the closed–vs–open contrast or the north–vs–south contrast.

Table 3.37 Correlation coefficient (with significance level where $p \leq 0.05$) between pairs of unstandardised environmental covariates and the contrasts between north and south zones and open and closed zones — for benthic invertebrate analysis.

	mud	carbonate	depth	habitat	year	north vs south	closed vs open
mud	1.000	–0.320 (< 0.001)	–0.100	–0.092	–0.144	–0.135	0.089
carbonate		1.000	0.400 (< 0.001)	0.086	0.092	0.100	–0.014
depth			1.000	–0.137	0.010	0.086	–0.096
habitat				1.000	–0.013	–0.134	–0.012
year					1.000	–0.125	–0.060

Benthic dredge invertebrates with a significant difference between zones closed and open to trawling

Of the 169 benthic invertebrate species analysed, we selected for closer examination the subset of 21 species that had a statistically significant difference between the closed and open zones either for log-transformed weight or for log-transformed number (usually both were significant). Table 3.38 shows the significance level for all environmental covariates and the closed–open difference, for log-transformed weight. Table 3.39 shows the corresponding estimate of the covariate coefficients. Table 3.40 and 3.41 give the significance level and estimated coefficients for log-transformed number.

There were 21 species with a statistically significant ($p \leq 0.05$) difference between the closed zone and the open zone: 12 were more abundant in the closed zone, 9 more abundant in the open zone.

The five species with the highest difference of abundance (on the $\log_{10}$ scale) in favour of the closed zone were: Crinoid sp.5 (0.273 for weight; 0.232 for number); *Scrupocellaris* sp. (0.260/0.180; Ophiuroid sp.34 (0.222/0.189); Crinoid sp.19 (0.187/0.210); and *Hyatina hyotis* (0.183/0.081). For Crinoid sp.5, approximately twice as many were found per station in the closed zone as in the open zone.

Crinoid sp.5 was moderately common (62 out of 157 stations), but most abundant offshore. It was found in greater quantities where the habitat index was high, there was more in the northern part of the open zone than in the southern part and there was a difference between the years. *Scrupocellaria* sp. was uncommon (20 stations). Its negative coefficients for mud and carbonate suggest it prefers sandy areas, yet it seems to be more abundant where the habitat index was high. Its abundance differed between the years. Ophiuroid sp.34 was uncommon (30 stations), and was more abundant offshore (significant negative coefficient for mud, non-significant but positive coefficient for carbonate) especially where the habitat index was high. Crinoid sp.19 was moderately common (45 stations), but more abundant offshore (negative coefficient for mud, positive coefficient for carbonate). *Hyatina hotis* was not common (26 stations), and was more abundant inshore (significant positive coefficient for mud, non-significant negative coefficient for carbonate).

The five species with the highest difference of abundance in favour of the open zone were: *Prionocidaris* sp.2 (–0.291/–0.104), Bryozoa sp.8 (–0.213/–0.082), Porifera sp.8 (–0.192/–0.086), Asteroid (mixed spp.) (–0.178/–0.124), and *Leucosia ocellata* (–0.148/–0.124). For *Prionocidaris* sp.2, back-transformation of the difference yields a ratio of twice as much biomass per station in the open zone as in the closed zone, though the ratio was lower for number per station.

Prionocidaris sp.2 was not common (29 stations out of 157), and showed no relationship with the environmental covariates but did differ between the years. Bryozoa sp.8 (17 stations) also showed no clear relationships with the environmental covariates. Porifera sp.8 was very uncommon (11 stations), and was found in shallow stations where the habitat index was high, and was more abundant in the north than the south. Asteroid (mixed spp.) were uncommon (19 stations), but most abundant in the northern part of the open zone. *Leucosia ocellata*, which was not common (35 stations), was found in greater quantities in inshore, muddy waters and differed significantly between the two years.

Table 3.38 Significance level for log-transformed weight for benthic invertebrate species with a significant ($p \leq 0.05$) difference between closed and open zones.

Species	*f*	mud	carbonate	depth	habitat	year	north vs south	closed vs open
Sponges								
Porifera sp.8	11	.895	.341	.026	.004	.158	<.001	.014
Porifera sp.121	12	.020	.548	.728	.047	.081	.801	.092
Crustaceans								
Leucosia ocellata	35	.001	.400	.515	.881	.006	.983	.022
Scyllarus demani	21	.575	.524	.315	.036	.259	<.001	.036
Spiropagurus sp.3	15	.389	.957	.825	.402	.002	.023	.037
Molluscs								
Cronia contracta	12	.438	.240	.349	.115	.021	.904	.036
Ctenocardia virgo	13	.050	.298	.021	.325	.887	.005	.050
Hyatina hyotis	26	.023	.053	.548	.102	.051	.138	.026
Modiolus ostentatus	18	<.001	.483	.508	.761	.007	.235	.043
Sepioid sp.3	11	.886	.825	.242	.705	.013	.009	.008
Bryozoans								
Bryozoa sp.8	17	.400	.062	.205	.402	.499	.442	.022
Bryozoa sp.18	14	.283	.853	.280	.009	.005	.686	.029
Scrupocellaria sp.	20	.003	.073	.609	.040	.010	.921	.003
Echinoderms								
Asteroid (mixed spp.)	19	.929	.624	.428	.203	.308	.018	.040
Crinoid sp.5	62	<.001	.004	.230	.044	.005	.004	.021
Crinoid sp.19	45	<.001	.007	.734	.755	.191	.575	.048
Ophiuroid sp.34	30	<.001	.249	.393	.003	.694	.900	.020
Pentaceraster sp.	13	.010	.825	.097	.107	.226	.291	.042
Prionocidaris sp.2	29	.792	.366	.142	.610	.038	.064	.012
Ascidians								
Ascidia sydneiensis	37	<.001	.745	.037	.338	.920	.535	.088
Pyura sacciformis	19	.002	.667	.087	.733	.516	.851	.019

Table 3.39 Estimated coefficient for log-transformed weight for benthic invertebrate species with a significant ($p \leq 0.05$) difference between closed and open zones

Species	mud	carbonate	depth	habitat	year	north vs south	closed vs open
Sponges							
Porifera sp.8	–0.022	0.190	–0.590	0.377	0.110	–0.221	–0.192
Porifera sp.121	–0.284	0.089	0.068	0.191	–0.100	–0.011	0.096
Crustaceans							
Leucosia ocellata	0.475	–0.140	–0.143	0.016	0.180	–0.001	–0.148
Scyllarus demani	–0.068	–0.094	–0.196	–0.201	0.065	0.157	–0.120
Spiropagurus sp.*3*	0.084	–0.006	0.034	–0.064	–0.141	–0.079	–0.095
Molluscs							
Cronia contracta	–0.088	0.163	–0.171	0.141	–0.125	0.005	0.112
Ctenocardia virgo	–0.211	0.136	–0.402	0.083	0.007	–0.108	–0.099
Hyatina hyotis	0.399	–0.412	–0.168	0.224	–0.161	0.092	0.183
Modiolus ostentatus	0.504	–0.120	–0.149	–0.034	–0.179	0.060	0.134
Sepiod sp.3	–0.013	–0.024	0.167	0.027	0.105	–0.084	–0.111
Bryozoans							
Bryozoa sp.8	–0.165	0.447	–0.399	0.129	–0.062	–0.054	–0.213
Bryozoa sp.18	–0.130	0.027	0.210	0.251	–0.164	0.017	0.125
Scrupocellaria sp.	–0.557	–0.410	0.154	0.304	–0.230	0.007	0.260
Echinoderms							
Asteroid (mixed spp.)	0.016	0.109	–0.233	–0.184	–0.088	0.156	–0.178
Crinoid sp.5	–1.879	0.898	–0.482	0.399	–0.336	–0.257	0.273
Crinoid sp.19	–1.208	0.672	0.110	0.049	–0.125	–0.040	0.187
Ophiuroid sp.34	–1.142	0.285	0.278	0.486	–0.038	–0.009	0.222
Pentaceraster sp.	–0.233	–0.024	–0.239	0.114	–0.051	–0.034	0.086
Prionocidaris sp.2	0.065	0.269	0.578	0.098	–0.241	0.162	–0.291
Ascidians							
Ascidia sydneiensis	0.888	–0.075	–0.637	–0.142	–0.009	0.042	0.151
Pyura sacciformis	0.355	0.058	0.307	0.030	0.034	–0.007	0.124

Table 3.40 Significance level for log-transformed number for benthic invertebrate species with a significant ($p \le 0.05$) difference between closed and open zones

Species	*f*	mud	carbonate	depth	habitat	year	north vs south	closed vs open
Sponges								
Porifera sp.8	11	.675	.272	.023	.006	.231	<.001	.019
Porifera sp.121	12	.011	.562	.530	.024	.020	.787	.045
Crustaceans								
Leucosia ocellata	35	.001	.393	.493	.970	.024	.992	.024
Scyllarus demani	21	.622	.726	.290	.033	.230	<.001	.025
Spiropagurus sp.3	15	.496	.517	.408	.215	<.001	.007	.023
Molluscs								
Cronia contracta	12	.580	.277	.443	.058	.017	.827	.043
Ctenocardia virgo	13	.087	.431	.052	.243	.953	.006	.031
Hyatina hyotis	26	.022	.296	.489	.073	.078	.154	.098
Modiolus ostentatus	18	<.001	.650	.933	.829	.004	.163	.070
Sepiod sp.3	11	.952	.713	.900	.475	.013	.005	.004
Bryozoans								
Bryozoa sp.8	17	.161	.108	.501	.193	.152	.493	.132
Bryozoa sp.18	14	.189	.823	.251	.008	.001	.639	.043
Scrupocellaria sp.	20	.002	.124	.631	.014	.001	.739	.001
Echinoderms								
Asteroid (mixed spp.)	19	.634	.824	.279	.178	.016	.023	.045
Crinoid sp.5	62	<.001	.001	.238	.042	.025	.002	.043
Crinoid sp.19	45	<.001	.009	.605	.772	.315	.364	.018
Ophuiroid sp.34	30	<.001	.285	.332	.001	.457	.840	.011
Pentaceraster sp.	13	.011	.850	.077	.092	.216	.194	.077
Prionocidaris sp.2	29	.803	.527	.147	.442	.050	.240	.094
Ascidians								
Ascidia sydneiensis	37	<.001	.887	.021	.241	.573	.379	.046
Pyura sacciformis	19	.001	.679	.099	.685	.471	.929	.025

Table 3.41 Estimated covariate coefficient for log-transformed number for benthic invertebrate species with a significant ($p \leq 0.05$) difference between closed and open zones

Species	mud	carbonate	depth	habitat	year	north vs south	closed vs open
Sponges							
Porifera sp.8	–0.032	0.104	–0.284	0.171	0.044	–0.101	–0.086
Porifera sp.121	–0.258	0.071	0.101	0.180	–0.111	–0.010	0.095
Crustaceans							
Leucosia ocellata	0.390	–0.121	–0.128	0.003	0.125	–0.000	–0.124
Scyllarus demani	–0.037	–0.032	–0.127	–0.126	0.042	0.102	–0.079
Spiropagurus sp.3	0.044	–0.051	0.086	–0.063	–0.113	–0.063	–0.069
Molluscs							
Cronia contracta	–0.045	0.107	–0.099	0.121	–0.092	0.006	0.077
Ctenocardia virgo	–0.143	0.080	–0.261	0.076	0.002	–0.083	–0.085
Hyatina hyotis	0.242	–0.133	–0.116	0.148	–0.087	0.053	0.081
Modiolus ostentatus	0.305	–0.039	–0.009	–0.012	–0.097	0.035	0.060
Sepioid sp.3	0.003	0.025	–0.011	0.031	0.065	–0.056	–0.076
Bryozoans							
Bryozoa sp.8	–0.164	0.229	–0.126	0.120	–0.079	–0.029	–0.082
Bryozoa sp.18	–0.153	0.032	0.215	0.247	–0.184	0.020	0.111
Scrupocellaria sp.	–0.368	–0.217	0.089	0.226	–0.183	–0.014	0.180
Echinoderms							
Asteroid (mixed spp.)	0.062	0.035	–0.228	–0.139	–0.150	0.107	–0.124
Crinoid sp.5	-1.781	0.989	–0.460	0.389	–0.259	–0.274	0.232
Crinoid sp.19	-1.179	0.603	0.156	0.043	–0.089	–0.061	0.210
Ophiuroid sp.34	–0.876	0.205	0.245	0.413	–0.055	–0.011	0.189
Pentaceraster sp.	–0.254	0.023	–0.282	0.131	–0.058	–0.046	0.082
Prionocidaris sp.2	–0.033	0.101	0.307	0.079	–0.122	0.055	–0.104
Ascidians							
Ascidia sydneiensis	0.645	0.023	–0.493	–0.122	–0.035	0.041	0.124
Pyura sacciformis	0.288	0.044	0.235	0.028	0.030	0.003	0.093

Assessment of the benthic dredge invertebrate community

For each covariate, we tabulated the percentage of species which had a significant result, for log-transformed weight and log-transformed number (Table 3.42 and 3.43). The percentage was tabulated for three frequency groups and for the full set of species that was analysed.

Mud was by far the best predictor in terms of the percentage of species for which this covariate was significant: 51% for weight (51% for number) overall; ranging from 30% (29%) for the '11–20' group to 80% (78%) for the '> 40' group. The year effect was significant in 24% (27%) of species and a similar result was obtained for the north–south difference. The common species ('> 40' group) had the highest percentage of significant results for the north–south difference: 48% (50%) compared with 18% (13%) and 23% (19%) for the common species groups. Carbonate, depth and the habitat index accounted for less variation than mud, year and north–south differences. Carbonate was significant for 12% (11%), depth for 15% (17%) and habitate for 16% (19%) of species. For carbonate, significant results were found in 23% (20%) of the '>

40' group but only 8% (7%) of the '11–20' group. The closed zone differed statistically from the open zone in only 11% (9%) of the species analysed. A higher percentage of species was significant for the '11–20' group than for the other two groups.

Table 3.42 Percentage of benthic invertebrate species with a significant result ($p \leq 0.05$), for each term in the analysis of covariance model, for log-transformed weight.

Frequency group	Number of species in group	Term in analysis of covariance model						
		mud (%)	carbonate (%)	depth (%)	habitat (%)	year (%)	north vs south (%)	closed vs open (%)
> 40	40	80	23	15	18	18	48	5
21–40	61	59	10	15	15	28	18	8
11–20	71	30	8	15	17	25	23	17
> 10	172	51	12	15	16	24	27	11

Table 3.43 Percentage of benthic invertebrate species with a significant result ($p \leq 0.05$), for each term in the analysis of covariance model, for log-transformed number.

Frequency group	Number of species in group	Term in analysis of covariance model						
		mud (%)	carbonate (%)	depth (%)	habitat (%)	year (%)	north vs south (%)	closed vs open (%)
> 40	40	78	20	18	20	18	50	5
21–40	61	59	8	18	15	28	13	7
11–20	71	29	7	16	23	31	19	14
> 10	172	51	11	17	19	27	24	9

Full details of the significance level and the estimated coefficient for all covariates and the difference between zones are given in Appendix 3.D.

The results of the multivariate analysis for benthic invertebrates are shown in Table 3.44 (log-transformed weight) and Table 3.45 (log-transformed number). In the groups of commoner species ('> 40', '21–40' and '11–20' groups), mud was highly statistically significant and clearly effective in removing 'noise' from the data. This was still the case when the largest possible group was analysed (the '> 14' group). For carbonate, statistically significant results were obtained for the two groups of common species ('> 40' and '21–40'). Depth was significant for all but the rarest ('4–6') group; for the latter the results were somewhat contradictory between log-transformed weight and log-transformed number. Depth was a worthwhile covariate to have included, but strangely was not significant for the most comprehensive ('> 14') group. The habitat index was highly effective for all groups except the '4–6' group. There was a clear difference between the years for all groups except the rarest ('4–6') group where log-transformed number had a significant result but log-transformed weight did not.

Table 3.44 Significance level for Wilks' lambda in multivariate analysis of covariance of log-transformed weight for benthic invertebrate species.

Frequency group	Number of species in group	Term in analysis of covariance model						
		mud	carbonate	depth	habitat	year	north vs south	closed vs open
> 40	40	<.0001	.0420	.0181	.0205	.0006	.0002	.6155
21–40	61	<.0001	.0175	.0198	<.0001	<.0001	.0054	.1951
11–20	71	.0097	.4565	.0011	.0504	<.0001	.0122	.1015
7–10	80	.1174	.0890	.0060	.0038	<.0001	.4983	.1040
4–6	128	.6275	.7101	.5334	.7814	.1002	.2950	.3236
> 14	131	.0345	.2149	.4694	.0071	.0225	.1762	.7035

Table 3.45 Significance level for Wilks' lambda in multivariate analysis of covariance of log-transformed number for benthic invertebrate species.

Frequency group	Number of species in group	Term in analysis of covariance model						
		mud	carbonate	depth	habitat	year	north vs south	closed vs open
> 40	40	<.0001	.0921	.0104	.0049	.0002	<.0001	.5110
21–40	60	<.0001	.0123	.0033	<.0001	<.0001	.0016	.5184
11–20	68	.0018	.1936	.0012	.0372	<.0001	.0063	.0550
6–10	78	.0585	.0086	.0455	.0019	.0003	.1851	.1032
3–5	127	.6835	.0960	.0843	.5252	.0024	.1516	.1750
>14	130	.0644	.2140	.7661	.0722	.0074	.1217	.5397

The difference in log-transformed biomass or abundance between the northern and southern sections of the open zone was highly significant for the three groups of commoner species ('> 40', '21–40' and '11–20' groups) and not significant for the rarer groups. For the '> 14' group the north–south difference was not significant.

No difference could be detected in log-transformed biomass between the closed and open zones. Presumably any such difference is much smaller than the north–south difference, especially as there is a larger set of samples for comparing closed with open than for comparing north and south sections of the open zone.

3.4 DISCUSSION

The GBRMPA Magnetic Island workshop had recommended that the Effects of Trawling study should take advantage of the area closed to trawling (Marine National Park B Zone) in the Far Northern Section of the GBR (Craik et al., 1989). This area, commonly known as the Green Zone because of its marine park zoning classification, covers around 10000 km^2 and is an extremely large area compared with most areas closed to fishing around the world. Comparison of such large areas was intended to assress ecosystem issues with respect to effects of trawling. The large size of the Green Zone is not necessarily an advantage given the variability in the area which includes the inshore lagoon and offshore shoals and reefs. However, this variability is a feature of the East Coast prawn fishery and restricting the study to a small area with little variation would not have been realistic.

Comparing the biota of areas that are closed to fishing with those that are open is an obvious way to measure the impact of fishing. However, this method is rarely used in effects of fishing studies. The main difficulty is to find an unfished area adjacent to a fished one. If an area is suitable for fishing, then there is a high probability that it will already be fished. Jennings and Kaiser (in press) point out that 'Since all marine ecosystems are now fished (with the exception of deep-sea abyssal systems), marine ecologists do not have access to large areas where the structure and and natural variability of systems can be studied and provide controls for fishing effects studies'. The Green Zone was open to fishing until its closure in 1985 — only six years before the start of the study — and so could not be regarded as completely unfished. Researchers generally have to deal with areas that were formerly fished but subsequently closed and presumed to have recovered. Examples include the Isle of Man closure in the Irish Sea (Brand et al., 1991) and several described in ICES (1996). Prena et al. (1996) described the site selection for an experiment on the Grand Banks off Newfoundland. Their criteria included that the site should not have been trawled or at least not for several years before the experiment and that it should be protected from external disturbance during the experiment. These criteria are difficult to achieve. Where closed areas are not available, an alternative approach is to compare areas that are subjected to different levels of fishing effort. Collie et al. (1996) used differences in the amount of disturbance of the seabed as a measure of the level of fishing effort to evaluate the effects of fishing on seabed fauna of the Georges Bank in the north-west Atlantic. This approach assumes that light levels of fishing have not caused major changes to the fauna – an assumption that may not be true for some highly vulnerable species such as large sponges. Sainsbury et al. (1997) for example estimate that between 43% and 95% of sponges were impacted by a single pass of a fish trawl.

Where closed areas are available, the preferred research approach has been to carry out experimental manipulative studies of the type described in Chapters 4 (BACI) and 5 (Repeat trawl). Comparisons between areas closed to fishing with those that are open to fishing, may be complicated by the unknown extent of fishing in the open area. Where data is available, there is still the problem of the uneven patterns of fishing effort in the fished areas. Unpublished data from trials carried out by the Queensland Fisheries Management Authority (QFMA) of a Vessel Monitoring System as well as data from continuous logging of GPS position on trawlers in the Northern Prawn Fishery (CSIRO unpublished data) show that prawn trawl effort is highly targeted. This results in some areas being heavily fished while others are either not fished at all or are only occasionally trawled. We do not have high resolution information on the distribution of trawling in the open areas adjacent to the Green Zone. This problem is discussed in Chapter 7 but it is obvious that a high degree of patchiness in the spatial pattern of fishing effort makes it difficult to compare fished and unfished areas.

When using an analysis of covariance model to compare communities in the open and closed zones, it would be desirable to have no correlations among the environmental covariates. If this were the case, each covariate would contribute independent information about the distribution of a given animal and the model would have greater predictive power. However, such a situation is rarely found in survey data. We found statistically significant correlations among some of the covariates in the study area. For example, there is a negative correlation between mud and calcium carbonate. This reflects the shift from fine sediments of terrigenous origin inshore to coarser sediments of biogenous origin offshore as has been reported elsewhere on the Great Barrier Reef (Alongi, 1990). There were also positive correlations between carbonate and depth, carbonate and rugosity, and depth and rugosity, and a negative correlation between mud and rugosity. This pattern of correlations is due to shallow water and a relatively level sea bottom inshore compared with deeper water and a more rugged profile of the sea bottom in the mid-shelf inter-reef area. We found however, that the environmental covariates have a similar distribution in the two open zones and the closed zone. Therefore any significant difference in biomass or abundance between zones could not simply be due to differences in the environment as expressed by the covariates used in this model.

The three main commercial prawn species (*Metapenaeus endeavouri, Penaeus esculentus and P. longistylus*) were more abundant in the area open to trawling than in the closed area. The non-commercial coral prawns by contrast were more abundant in the closed area. We do not know whether this is a consequence of trawling or reflects a distribution independent of trawl effort.

The fish species *Lethrinus genivittatus* was significantly more abundant in the Green Zone than the open zone for both the fish trawls and the prawn trawls. Several Upeneus species were also significantly more abundant in the Green Zone. By contrast, Saurida and Synodus species were more abundant in the zone open to trawling. Saurids were one of the genera that showed population increases following the development of an intensive fish trawl fishery in the Gulf of Thailand. Their relative abundance nearly doubled in around 10 years (summarised in Longhurst and Pauly, 1987) and they are regarded as being a group that appears to benefit from trawling.

Amongst the benthic invertebrates, the group showing the largest difference was the sponges (from bycatch). They were 1.6 times more abundant numerically and eight times more abundant by weight in the closed area. This indicates that on average, the sponges caught in bycatch in the closed area were larger than those in the open area. No consistent, strong patterns were seen the sponge species caught by the dredge.

While there are interesting results for a few species, overall the bycatch, fish trawl and benthic dredge communities appear to differ very little between the areas closed and open to trawling. Only about 10 percent of species or groups showed a statistically significant difference (p • 0.05). Many more species showed a significant difference between the open areas to the north and south of the closed zone: approximately 30 percent of bycatch species or groups, 20 percent of fish trawl species and 25 percent of benthic invertebrates.

Furthermore, even across different species of delicate fauna such as sponges and bryozoans, there was no consistent tendency for reduced numbers of animals in the areas open to trawling.

Species with a significant difference between the open and closed areas divided more or less evenly into those more abundant in the closed area and those more abundant in the open area. Seven species or groups of bycatch were more abundant in the closed area; five were more abundant in the open area. Nine species of fish captured in the fish trawl were more abundant in the closed area; six were more abundant in the open area. Twelve benthic invertebrate species were more abundant in the closed area; nine were more abundant in the open area.

In order to gain an overview of the differences among zones, we have presented the data graphically for all species or groups of prawns, bycatch, and catch from fish trawl and benthic dredge (Figures 3.01 to 3.08). The X–axis on each figure represents the difference between the mean for the open area north of the Green Zone and the average in the northern and southern open areas ('north vs south half difference'). The Y–axis represents the difference between the mean for the closed area and the average of the two open areas ('closed vs open half difference'). For example, *Penaeus longistylus* (Figures 3.01 and 3.02) was found in larger quantities in the open area to the north of the Green Zone than in the open area to the south, so it appears on the right-hand side of the figure. Similarly, it was found in smaller quantities inside the Green Zone than in the areas open to trawling, so it appears at the bottom of the figure. Species with a significant closed-vs-open difference are identified by name on the figures.

Two lines are superimposed on Figures 3.01 to 3.08, showing coordinates for which the closed-vs-open half-difference is either equal to, or opposite and equal to, the north-vs-south half-difference. These lines partition the figure into four triangular sectors. For species that appear in the top or bottom sectors, the closed-vs-open half-difference is larger than the north-vs-south half-difference. If there were a substantial difference between the open and closed zones due to trawling, one would find relatively few species in the left-hand and right-hand sectors. Most species would probably appear in the top, where the biomass or abundance is higher in the closed zone than the open and the difference in biomass between the closed and open zones is much greater than the difference between the open zones north and south of the closed zone. Prawns are the only group of animals with most species in the top or bottom sectors. These may have arisen from the impact of trawling, or it may be that the Green Zone was always fished more lightly than the open areas. In any case, fourteen species is a small number data set from which to infer a systematic pattern. The other three data sets have a substantial number of species in the left-hand and right-hand sectors. Furthermore, the proportion of species in these sectors with a statistically significant north-vs-south difference (blue or red dots) is appreciably higher than the proportion of species in the top and bottom sectors with a statistically significant closed-vs-open difference (orange or red dots). These results provide little evidence of an effect of trawling, and suggest much more strongly that the distribution of species varies naturally in the north-south direction as well as across the shelf.

The absence of a clear difference between the areas closed to trawling and the adjacent open areas cannot be interpreted as indicating that trawling has no effect. The results of the Repeat Trawl experiment described in Chapter 5 show that on average a prawn trawl removes around 10% of the epibenthos. In that case, why were the results of the comparison between the closed and open areas so equivocal. We offer two possible reasons.

1. From the outset, this was not a comparison between an untrawled and a trawled area. Analysis of recent logbook data where fishing effort was recorded on a 6 x 6 n.mile grid basis shows that in 1996, the equivalent in boat-days of 750 hours of trawling was reported for several grids in the Green Zone. We know that illegal trawling is taking place in the

Green Zone and that trawl time in the Zone is attributed to the adjacent open area (Gribble and Roberston, 1998). Additionally, we know from logbook records that the intensity of trawling in the areas open to fishing is low. A total of 5250 hours of trawling took place in the open part of the study area. But nearly 40% of the grids in the open area were not trawled at all and only 20% had effort equivalent to once-over coverage or more. An additional complication may result from the seabed fauna not being uniformly distributed. Most trawling is in the inshore lagoon but our study included the offshore inter-shoal area that is subject to little effort. We conclude that this is not a comparison between a trawled and an untrawled area, but rather a comparison between two areas that, with the exception of some relatively small 'hotspots', are lightly trawled. Consequently we might not expect to find a difference that could be attributed to trawling.

2. We have found many species with a significant difference between the open area to the south of the Green Zone and that to the north. This is well illustrated in Figures 3.03 to 3.08. These differences indicate that significant differences in fauna occur over relatively small distances in the GBR even along the north south axis – a direction with greater uniformity than the east west which shows considerable zonation (see Chapter 2). Given this high degree of variation, we could reasonably expect differences between the Green Zone and adjacent areas that are simply a result of this inherent variability and are not related to an effect of trawling.

The complexity and variation of the study area makes it difficult to carry out comparisons between its component parts. The power of the comparison was sufficient on average to detect a reduction of 60%. As pointed out in the Methods section of this Chapter, the power was expected to be adequate when the study was designed, given the prevailing general perception of the magnitude of the impact of prawn trawling. At the beginning of this study, there was a wide-spread perception that trawling was extremely damaging to the seabed environment and that effect sizes would be large, although rigorous quantitative information was scarce. For example, Sainsbury et al's (1997) video observations indicated trawl gear impacting around 90% of large sponges. Consequently, we anticipated designing for the capability to detect large effect sizes of 10-fold or less. However, the much lower impact of a prawn trawl, the low level of effort in the open area together with the illegal effort in the closed area have combined to give a situation where it was not possible to identify an effect that could be unambiguously attributed to trawling, at least not by comparing areas that are closed or open to fishing.

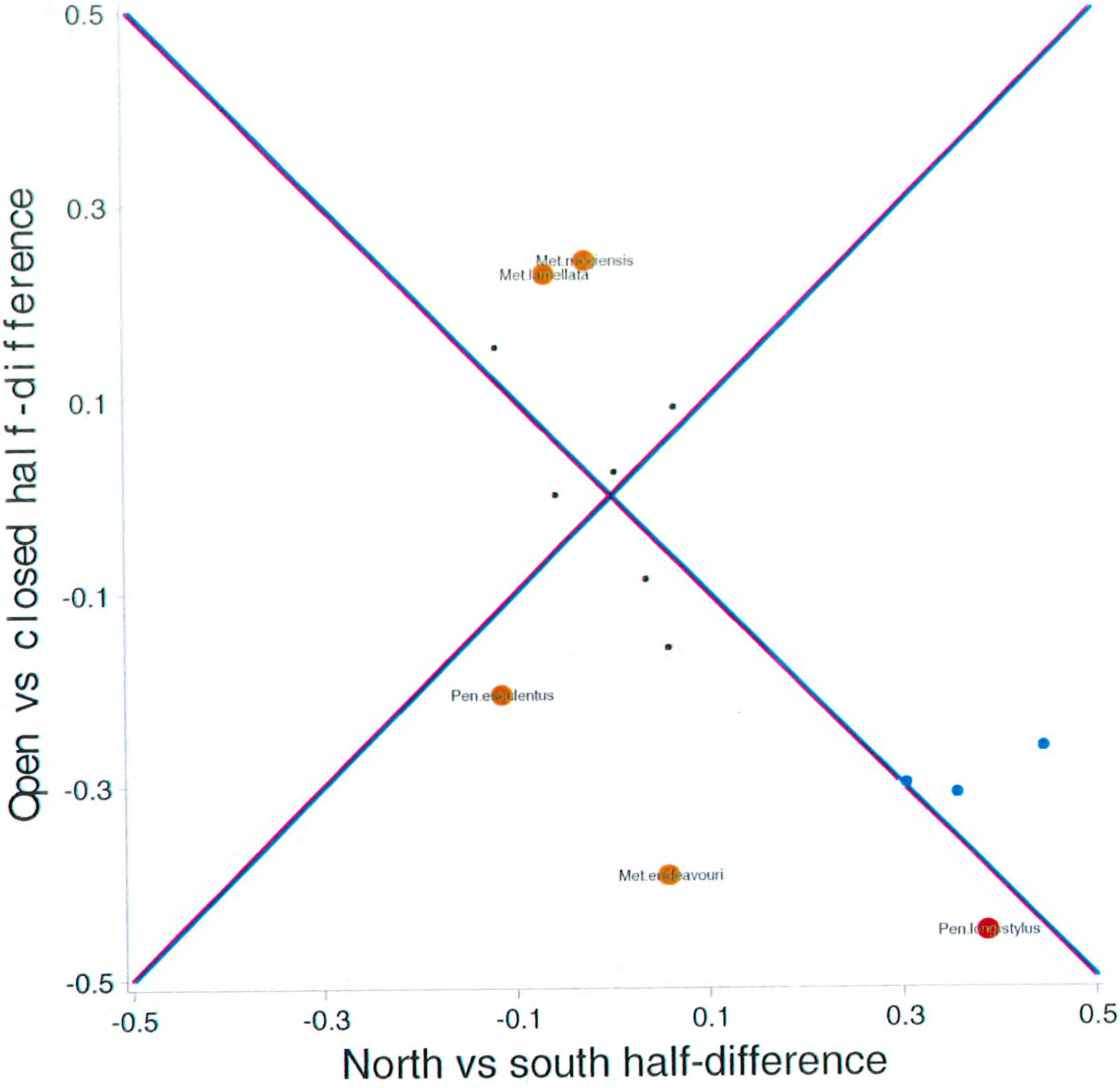


Figure 3.01 Closed-vs-open difference and north-vs-south difference for prawn species from analysis of log-transformed weight. Named red dots show species with both effects significant; named orange dots those with significant closed-vs-open difference; blue dots those with significant north-vs-south difference; black dots those with no significant difference for either effect.

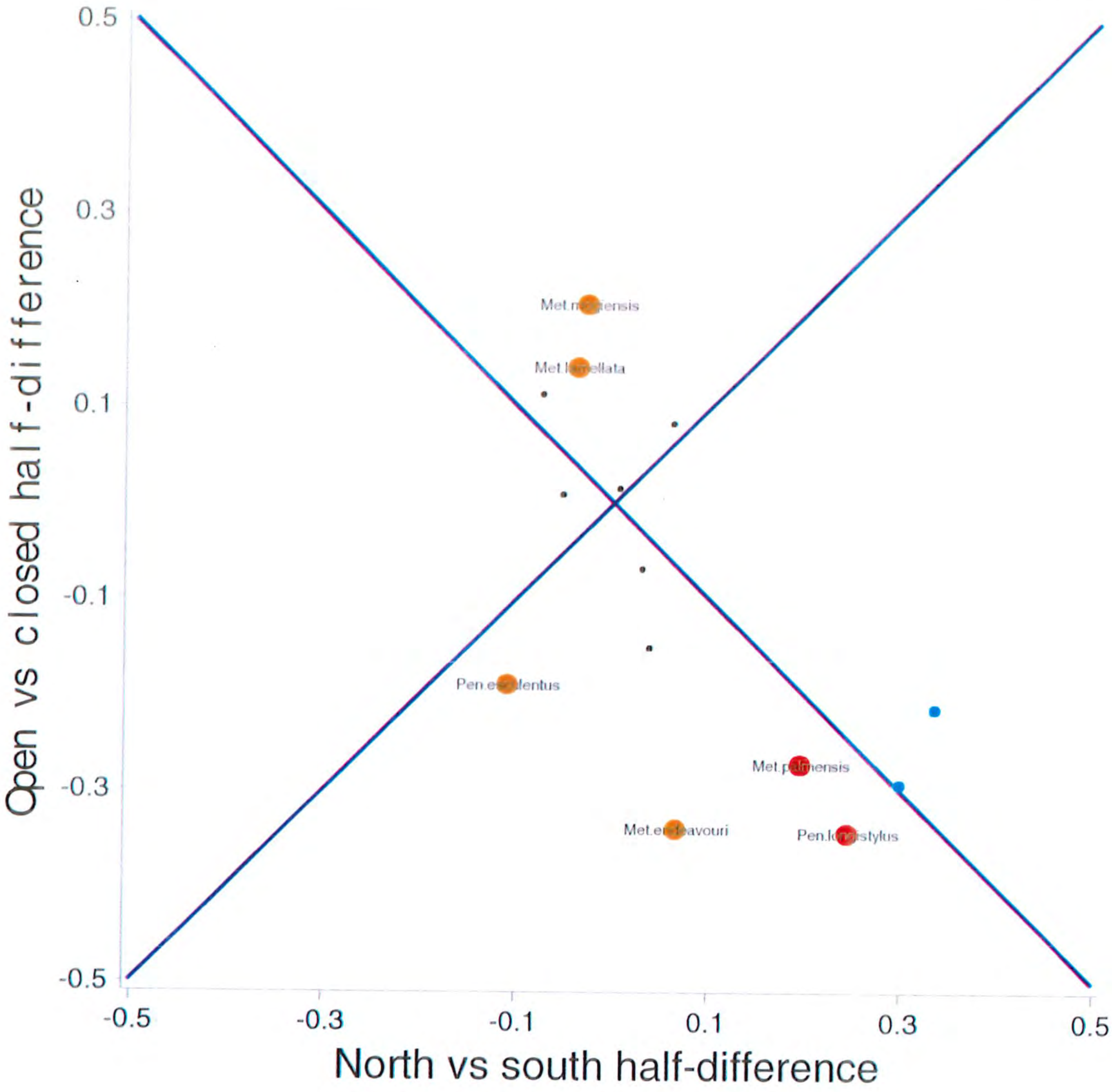


Figure 3.02 Closed-vs-open difference and north-vs-south difference for prawn species from analysis of log-transformed number. Named red dots show species with both effects significant; named orange dots those with significant closed-vs-open difference; blue dots those with significant north-vs-south difference; black dots those with no significant difference for either effect.

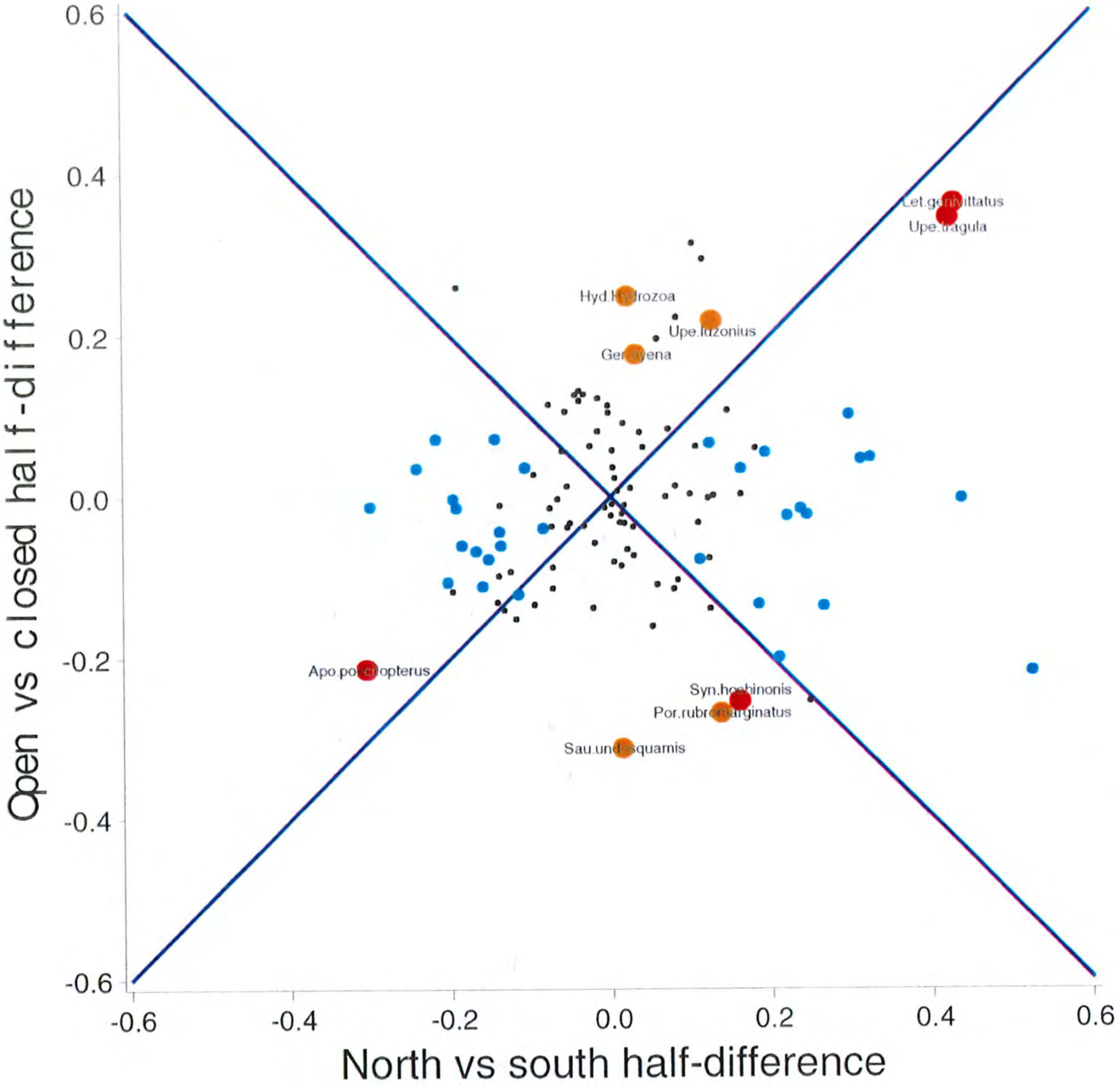


Figure 3.03 Closed-vs-open difference and north-vs-south difference for bycatch species or groups from analysis of log-transformed weight. Named red dots show species with both effects significant; named orange dots those with significant closed-vs-open difference; blue dots those with significant north-vs-south difference; black dots those with no significant difference for either effect.

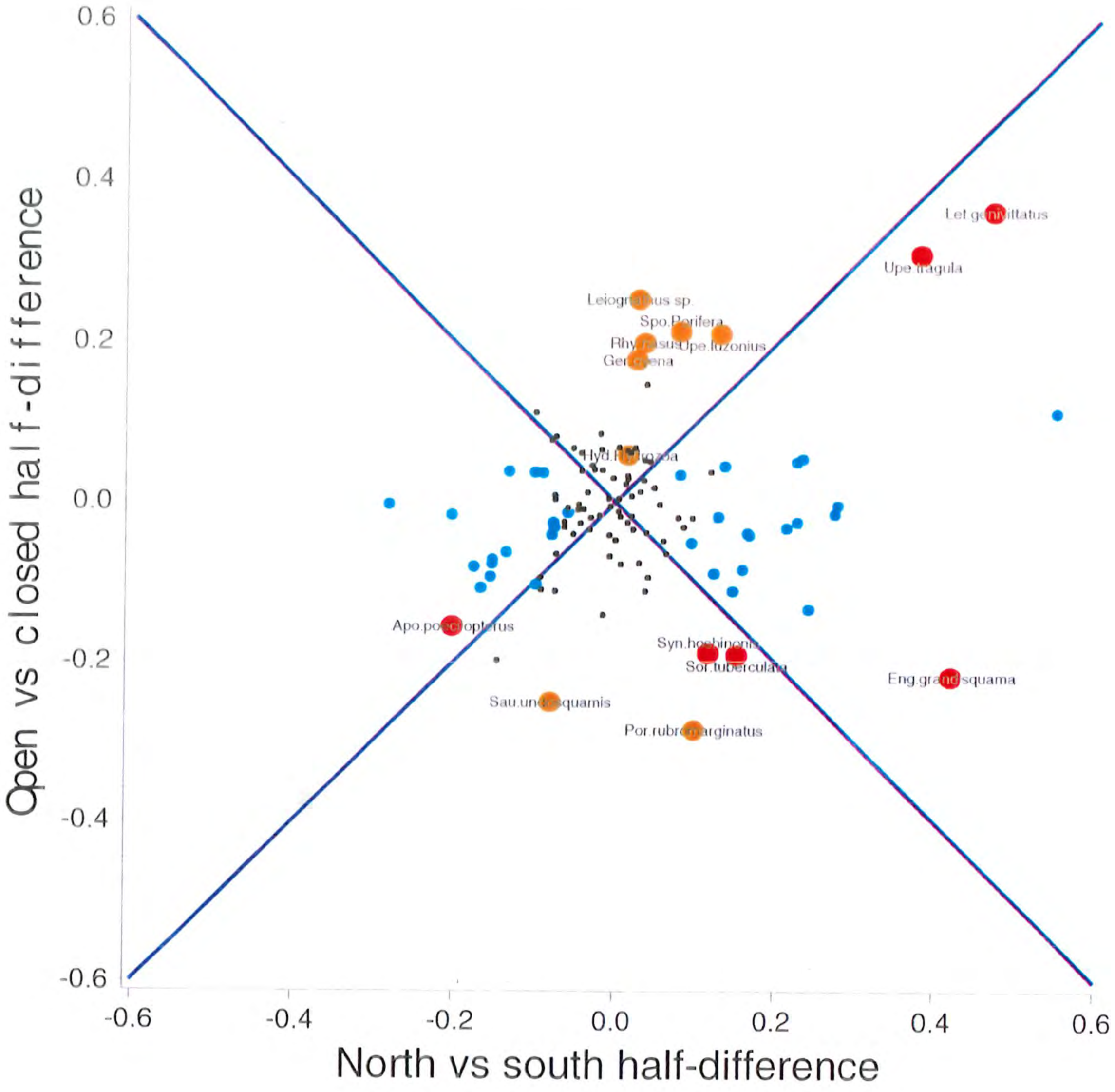


Figure 3.04 Closed-vs-open difference and north-vs-south difference for bycatch species or groups from analysis of log-transformed number. Named red dots show species with both effects significant; named orange dots those with significant closed-vs-open difference; blue dots those with significant north-vs-south difference; black dots those with no significant difference for either effect.

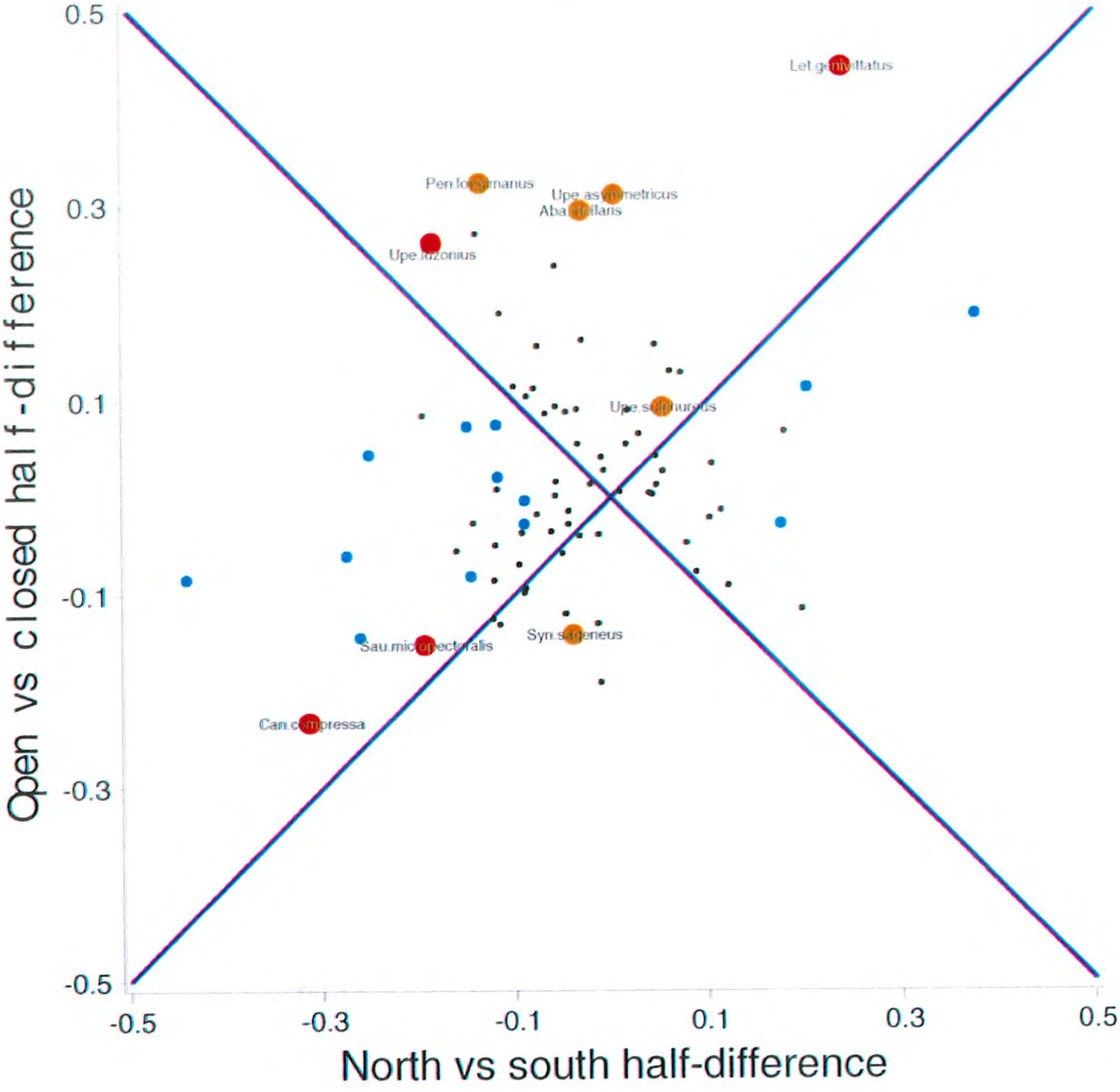


Figure 3.05 Closed-vs-open difference and north-vs-south difference for fish species in the fish trawl from analysis of log-transformed weight. Named red dots show species with both effects significant; named orange dots those with significant closed-vs-open difference; blue dots those with significant north-vs-south difference; black dots those with no significant difference for either effect.

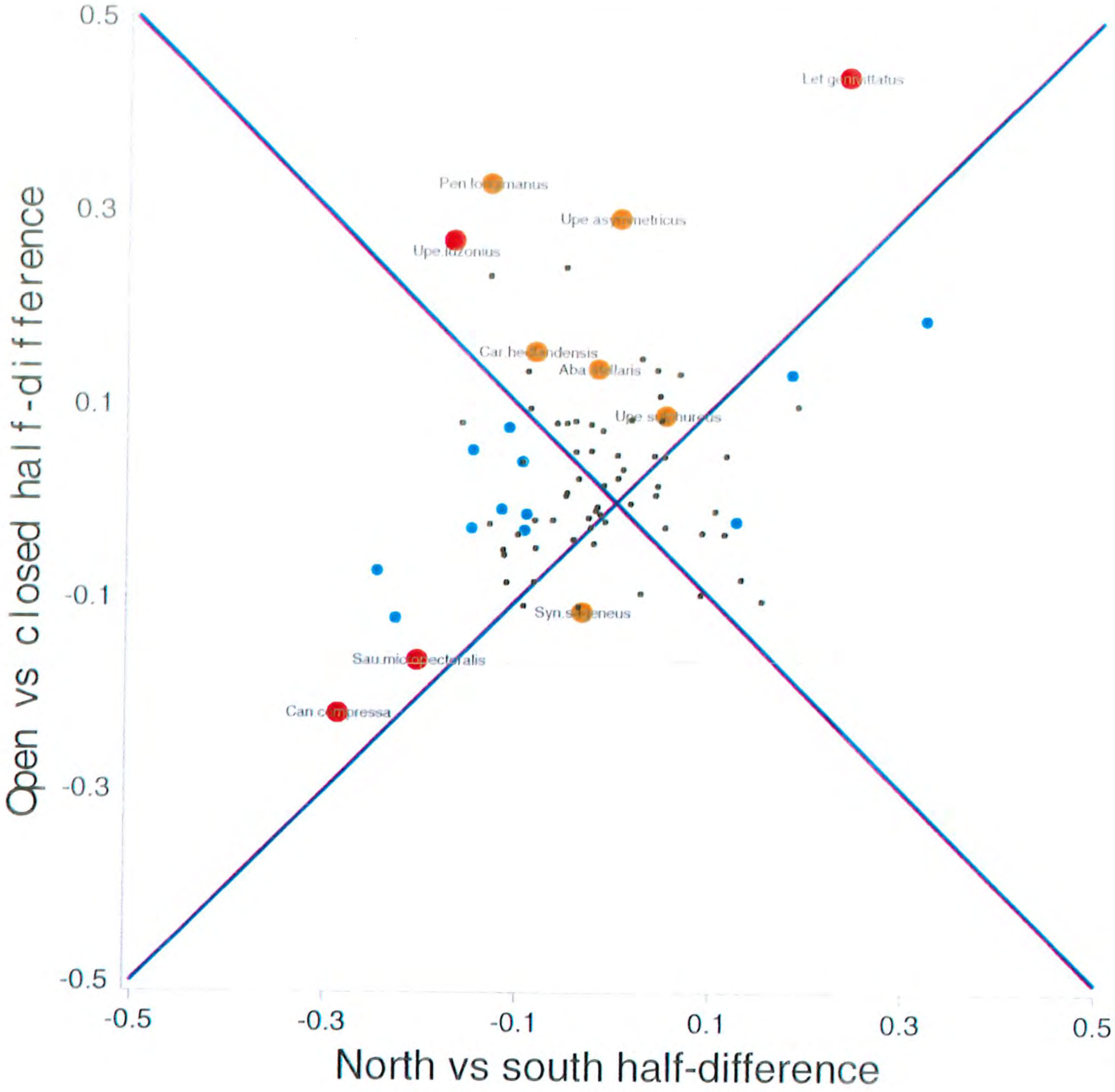


Figure 3.06 Closed-vs-open difference and north-vs-south difference for fish species in the fish trawl from analysis of log-transformed number. Named red dots show species with both effects significant; named orange dots those with significant closed-vs-open difference; blue dots those with significant north-vs-south difference; black dots those with no significant difference for either effect.

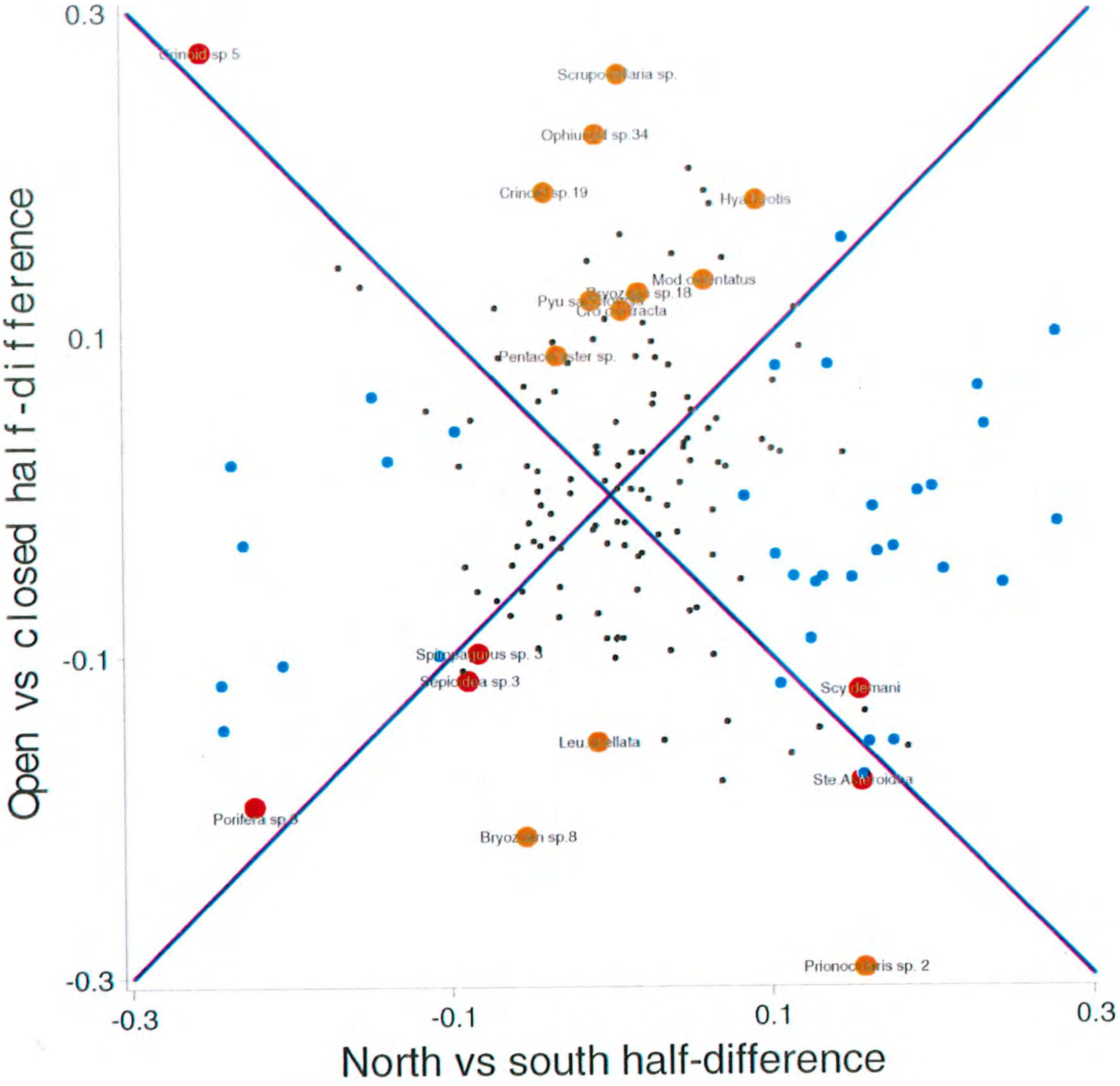


Figure 3.07 Closed-vs-open difference and north-vs-south difference for benthic invertebrate species or groups from analysis of log-transformed weight. Named red dots show species with both effects significant; named orange dots those with significant closed-vs-open difference; blue dots those with significant north-vs-south difference; black dots those with no significant difference for either effect.

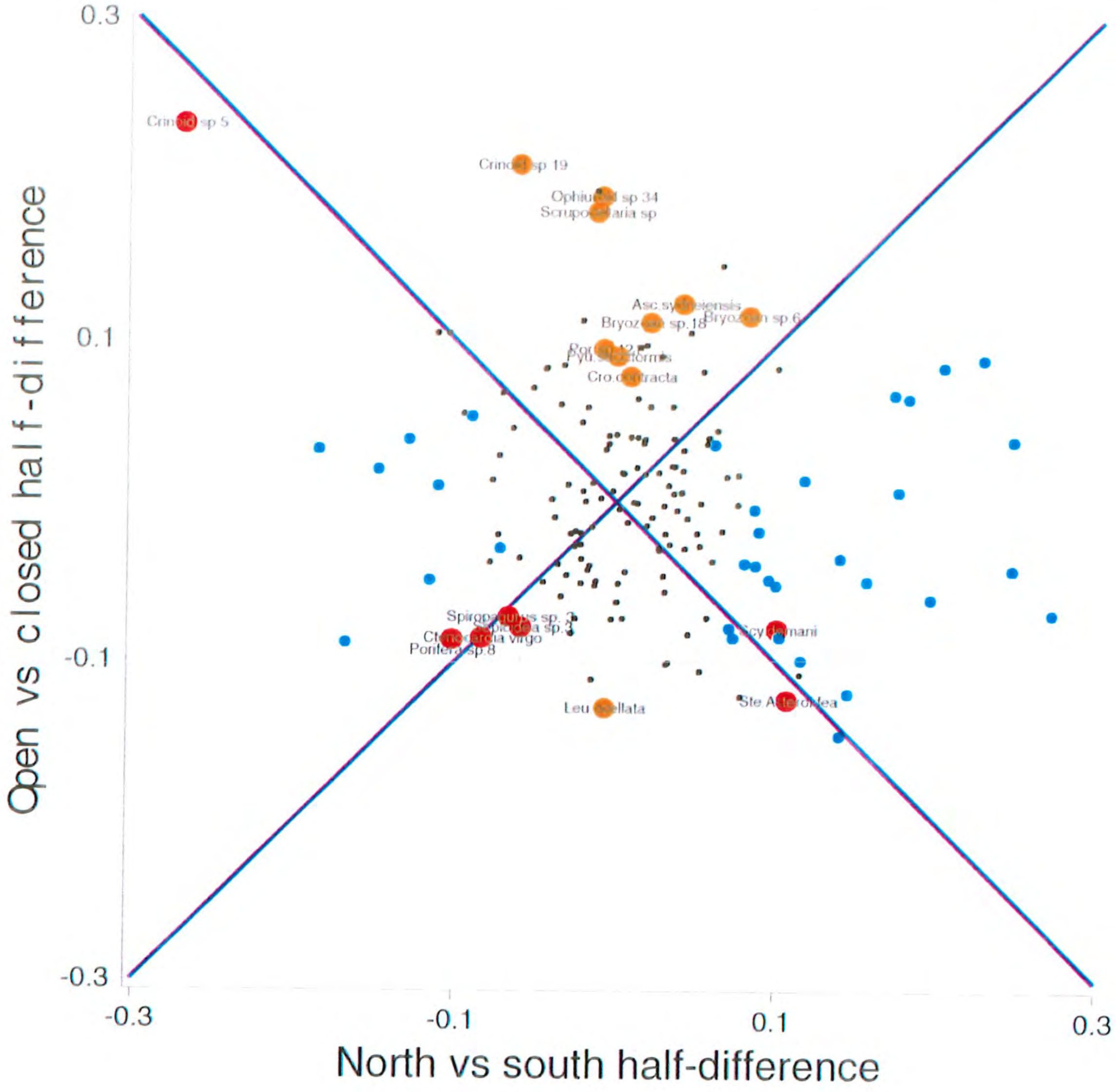


Figure 3.08 Closed-vs-open difference and north-vs-south difference for benthic invertebrate species or groups from analysis of log-transformed number. Named red dots show species with both effects significant; named orange dots those with significant closed-vs-open difference; blue dots those with significant north-vs-south difference; black dots those with no significant difference for either effect.

APPENDIX.3.A ANTICIPATED MINIMUM DETECTABLE DIFFERENCES (δ) AT THE CLASS AND SPECIES LEVEL

Table App.3.A.1 Variances, cost-benefit analysis and anticipated minimum detectable difference (δ) for taxa sampled by the prawn trawl in proposed closed-vs-open comparisons (only negative effects have been tabulated) for ($1\text{-}\beta=0.80$, $\alpha=0.05$, $k'=2$, $n'=50$, $\nu=90$, $\gamma=2.832$). Note: δ and zone means are estimated with error and are reported in $\log_{10}$(gms) units; back-transformed (=geometric) means (gms). This effect size is also presented as a relative biomass (back-transformed) ratio (%). Cohen's ESI = 0.283 in each case.

Class/species	S^2stat	S^2loc	cost-benefit stn/loc	recalculated S^2	δ	mean in closed zone	%
Prawn species							
Metapenaeopsis palmensis	0.148	0.234	0.421	0.381	0.350	–0.010	45
Metapenaeopsis rosea	0.358	0.512	0.443	0.871	0.528	–0.541	30
Metapenae endeavouri	0.136	0.307	0.352	0.444	0.377	1.644	42
Penaeus esculentus	0.032	0.135	0.260	0.167	0.232	1.801	59
Penaeus latisulcatus	0.213	0.167	0.597	0.380	0.349	0.808	45
Penaeus longistylus	0.348	0.157	0.789	0.505	0.402	0.882	40
Trachypenaeus anchoralis	0.354	0.117	0.919	0.471	0.389	–0.766	41
Trachypenaeus granulosis	0.433	0.647	0.433	1.080	0.589	–0.166	26
Average			0.527		0.402		41
Prawn bycatch classes							
Algae	0.045	0	6.316	0.045	0.120	0.046	76
Porifera	2.110	0.305	1.393	2.415	0.880	1.243	13
Hydrozoa	0.355	0.099	1.000	0.455	0.382	0.649	42
Octocorallia	0.592	0.125	1.152	0.717	0.479	1.284	33
Zoantharia	0.081	0.005	2.092	0.087	0.167	0.716	68
Polycheatea	0.005	0	1.777	0.005	0.041	0.615	91
Decapoda	0.036	0.072	0.372	0.107	0.186	2.245	65
Gastropoda	0.004	0.001	1.000	0.005	0.041	< 0.001	91
Bivalvia	0.107	0.252	0.345	0.359	0.340	1.652	46
Cephalopoda	0.250	0.030	1.535	0.280	0.300	2.005	50
Bryozoans	0.005	0	1.630	0.005	0.041	1.970	91
Crinoidea	0.371	0.104	1.000	0.475	0.390	0.949	41
Asteroidea	0.653	0.313	0.764	0.966	0.557	0.245	28
Echinoidea	0.298	0.085	0.990	0.384	0.351	0.395	45
Holothurioidea	0.557	0.156	1.000	0.713	0.478	–0.050	33
Ophiuroidea	0.141	0.039	1.000	0.180	0.241	0.681	57
Ascidiacea	0.192	0.054	1.000	0.245	0.281	0.296	52
Average			1.433		0.310		54

Class/species	S^2stat	S^2loc	cost-benefit stn/loc	recalculated S^2	δ	mean in closed zone	%
Prawn bycatch by species							
Apistus carinatus	0.148	0.20	0.454	0.349	0.334	1.609	46
Apogon ellioti	0.268	0.23	0.570	0.499	0.400	1.216	40
Apogon fasciatus	0.478	0.12	1.056	0.598	0.438	1.289	36
Callionymus grossi	0.177	0.16	0.564	0.333	0.327	1.342	47
Choerodon cephalotes	0.200	0.15	0.610	0.350	0.335	1.756	46
Choerodon sp.2	0.399	0.05	1.574	0.444	0.377	1.623	42
Engyprosopon grandisquama	0.186	0.27	0.436	0.460	0.384	1.134	41
Euristhmus nudiceps	0.045	0.24	0.231	0.281	0.300	1.816	50
Lagocephalus sceleratus	0.185	0.05	1.000	0.237	0.276	1.598	53
Lethrinus genivittatus	0.064	0.12	0.379	0.187	0.245	3.270	57
Nemipterus furcosus	0.072	0.07	0.519	0.147	0.217	2.949	61
Nemipterus peronii	0.265	0.07	1.000	0.339	0.330	1.750	47
Paramonacanthus choirocephalus	0.153	0.08	0.714	0.237	0.275	1.914	53
Paramonacanthus japonicus	0.136	0.10	0.629	0.232	0.273	1.963	53
Pentapodus paradiseus	0.401	0.02	2.347	0.422	0.368	2.139	43
Priacanthus tayenus	0.329	0.07	1.116	0.403	0.360	1.969	44
Pseudorhombus diplospilus	0.278	0.05	1.298	0.324	0.322	1.584	48
Pseudorhombus spinosus	0.402	0.16	0.830	0.565	0.426	1.404	38
Rhynchostracion nasus	0.632	0.18	1.000	0.808	0.509	1.370	31
Saurida undosquamis	0.142	0.03	1.078	0.176	0.238	2.364	58
Scolopsis taeniopterus	0.126	0.21	0.406	0.339	0.330	2.250	47
Selaroides leptolepis	0.537	0.06	1.584	0.597	0.438	1.089	36
Siganus canaliculatus	0.451	0.19	0.818	0.640	0.453	1.376	35
Sorsogona tuberculata	0.113	0.49	0.255	0.602	0.439	1.019	36
Suggrundus isacanthus	0.084	0.07	0.585	0.152	0.221	1.896	60
Torquigener pallimaculatus	0.197	0.10	0.730	0.301	0.310	1.720	49
Upeneus tragula	0.266	0.23	0.572	0.493	0.398	2.635	40
Portunus rubromarginatus	0.150	0.06	0.820	0.213	0.261	1.782	55
Portunus tenuipes	0.206	0.21	0.519	0.419	0.367	1.721	43
Thenus orientalis	0.349	0.29	0.579	0.641	0.454	1.683	35
Amussiidae	0.211	0.20	0.549	0.406	0.361	1.589	44
Sepioidae	0.432	0.18	0.818	0.613	0.444	1.391	36
Average			0.801		0.350		45

Table App.3.A.2 Variances, cost-benefit analysis and anticipated minimum detectable difference (δ) for taxa sampled by the fish trawl in proposed closed-vs-open comparisons (only negative effects have been tabulated) for ($1-\beta=0.80$, $\alpha=0.05$, $k'=2$, $n'=50$, $\nu=90$, $\gamma=2.832$). Note: δ and zone means are estimated with error and are reported in $\log_{10}$(gms) units; back-transformed (=geometric) means (gms). This effect size is also presented as a relative biomass (back-transformed) ratio (%). Cohen's ESI = 0.283 in each case.

Class/species	S^2stat	S^2loc	cost-benefit stn/loc	recal-culated S^2	δ	mean in closed zone	%
Fish Trawl Families							
Clupeidae	0.983	0.59	0.684	1.571	0.710	1.370	19
Synodontidae	0.230	0.19	0.582	0.421	0.367	2.674	43
Fistulariidae	0.192	0.13	0.654	0.318	0.320	1.889	48
Priacanthidae	0.214	0.06	1.000	0.273	0.296	2.503	51
Carangidae	0.664	0.06	1.743	0.725	0.482	3.482	33
Leiognathidae	0.285	0.23	0.595	0.510	0.404	2.831	39
Nemipteridae	0.333	0.28	0.578	0.612	0.443	3.653	36
Gerreidae	0.266	0.34	0.469	0.604	0.440	2.042	36
Lethrinidae	0.139	0.43	0.301	0.568	0.427	4.092	37
Mullidae	0.485	0.44	0.557	0.922	0.544	2.696	29
Labridae	0.631	0.15	1.078	0.783	0.501	2.395	32
Siganidae	0.435	0.35	0.588	0.787	0.502	2.605	31
Scombridae	0.321	0.13	0.825	0.453	0.381	2.671	42
Balistidae	0.574	0.16	1.000	0.735	0.485	2.172	33
Tetraodontidae	0.487	0.10	1.164	0.587	0.434	2.646	37
			0.788		0.449		36
Fish Trawl species							
Alepes sp.	0.341	0.10	1.000	0.436	0.374	2.378	42
Carangoides caeruleopinnatus	0.334	0.22	0.645	0.559	0.423	1.974	38
Carangoides gymnostethus	0.243	0.08	0.928	0.322	0.321	1.664	48
Carangoides hedlandensis	0.337	0.09	1.000	0.431	0.372	2.158	42
Carangoides humerosus	0.164	0.01	2.229	0.173	0.236	2.047	58
Choerodon cephalotes	0.483	0.13	1.005	0.616	0.445	2.009	36
Choerodon sp.2	0.522	0.13	1.052	0.653	0.458	1.728	35
Diagramma pictum	0.857	0.01	4.133	0.871	0.529	1.960	30
Echeneis naucrates	0.548	0.15	1.000	0.702	0.475	1.537	34
Fistularia petimba	0.287	0.09	0.955	0.375	0.347	1.546	45
Gerres oyena	0.34	0.15	0.793	0.491	0.397	1.906	40
Herklotsichthys lippa	0.257	0.07	1.000	0.328	0.325	1.400	47
Leiognathus bindus	0.525	0.36	0.638	0.886	0.533	1.741	29
Lagocephalus sceleratus	0.343	0.08	1.074	0.426	0.370	1.800	43
Leiognathus leuciscus	0.836	0.08	1.664	0.921	0.544	0.621	29
Leiognathus sp.	0.379	0.26	0.644	0.634	0.451	2.497	35
Lethrinus genivittatus	0.155	0.40	0.328	0.557	0.423	3.979	38
Nemipterus furcosus	0.482	0.22	0.783	0.701	0.474	2.929	34
Nemipterus hexodon	0.293	0.07	1.089	0.362	0.341	1.690	46
Nemipterus peronii	0.108	0.13	0.492	0.234	0.274	1.675	53
Paramonacanthus japonicus	0.371	0.01	3.579	0.379	0.349	1.308	45
Pentapodus paradiseus	0.422	0.38	0.557	0.803	0.508	2.542	31
Pentaprion longimanus	0.235	0.28	0.488	0.512	0.405	1.538	39
Priacanthus tayenus	0.443	0.12	1.000	0.567	0.426	2.105	37
Pristotis jerdoni	0.391	0	7.609	0.393	0.355	1.586	44

Class/species	**S^2stat**	**S^2loc**	**cost-benefit stn/loc**	**recal-culated S^2**	**δ**	**mean in closed zone**	**%**
Rastrelliger kanagurta	0.159	0.04	1.000	0.203	0.255	2.092	56
Saurida undosquamis	0.244	0.17	0.636	0.413	0.364	2.670	43
Scolopsis taeniopterus	0.261	0.28	0.510	0.541	0.417	1.737	38
Scomberomorus queenslandicus	0.143	0.14	0.528	0.287	0.304	2.828	50
Selar boops	0.597	0.33	0.716	0.923	0.544	2.138	29
Selaroides leptolepis	0.674	0.15	1.141	0.819	0.513	3.160	31
Siganus canaliculatus	0.445	0.38	0.573	0.825	0.514	2.577	31
Sphyraena forsteri	0.687	0.19	1.000	0.879	0.531	1.503	29
Torquigener pallimaculatus	0.56	0.18	0.945	0.736	0.486	1.893	33
Upeneus luzonius	0.206	0.29	0.448	0.494	0.398	2.114	40
Upeneus tragula	0.409	0.12	0.996	0.525	0.410	1.262	39
Average			1.218		0.422		39

Table App.3.A.3 Variances, cost-benefit analysis and anticipated minimum detectable difference (δ) for taxa sampled by the benthic dredge in proposed closed-vs-open comparisons (only negative effects have been tabulated) for (1-β=0.80, α=0.05, k'=2, n'=50, ν=90, γ =2.832). Note: δ and zone means are estimated with error and are reported in $\log_{10}$(gms) units; back-transformed (=geometric) means (gms). This effect size is also presented as a relative biomass (back-transformed) ratio (%). Cohen's ESI = 0.283 in each case.

Class/species	S^2stat	S^2loc	cost-benefit stn/loc	recal-culated S^2	δ	mean in closed zone	%
Benthic Dredge Classes							
Porifera	1.582	0.059	2.751	1.640	0.725	2.909	19
Hydrozoa	0.830	0.218	1.032	1.048	0.580	0.920	26
Octocorallia	0.489	0.024	2.405	0.512	0.405	2.100	39
Zoantharia	0.336	0.148	0.797	0.484	0.394	2.458	40
Cirripedia	0.074	0.081	0.505	0.155	0.223	−0.232	60
Decapoda	0.207	0.058	1.000	0.265	0.292	2.042	51
Gastropoda	0.270	0.111	0.827	0.381	0.350	1.903	45
Bivalvia	0.239	0.403	0.407	0.641	0.454	2.233	35
Cephalopoda	0.123	0.087	0.628	0.210	0.260	1.353	55
Bryozoans	0.988	0.022	3.560	1.009	0.569	1.712	27
Crinoidea	0.630	0.176	1.000	0.806	0.509	2.393	31
Asteroidea	0.396	0.440	0.502	0.836	0.518	2.109	30
Echinoidea	0.907	0.252	1.004	1.158	0.610	1.893	25
Holothurioidea	1.243	0.249	1.181	1.492	0.692	2.205	20
Ophiuroidea	0.709	0.024	2.853	0.734	0.485	0.826	33
Ascidiacea	0.420	0.159	0.859	0.579	0.431	2.583	37
Average			1.237		0.451		37
Benthic dredge species							
Alcyonarian sp.1	0.860	0.063	1.961	0.922	0.544	0.704	29
Flabellum sp.1	0.299	0.123	0.824	0.422	0.368	0.482	43
Fungia sp.1	0.275	0.121	0.798	0.396	0.356	1.399	44
Sphaenopus sp.1	0.502	0.180	0.884	0.682	0.468	1.698	34
Portunus rubromarginatus	0.672	0.081	1.521	0.753	0.492	0.769	32
Portunus tenuipes	0.183	0.119	0.656	0.302	0.311	0.922	49
Chicoreus cervicornis	0.142	0.117	0.583	0.259	0.289	0.442	51
Amusium pleuronectes	0.328	0.092	1.000	0.420	0.367	0.787	43
Melaxinia vitrea	0.160	0.116	0.623	0.276	0.297	0.463	50
Crinoid sp.15	0.464	0.276	0.686	0.741	0.487	1.003	33
Crinoid sp.17	0.567	0.023	2.611	0.590	0.435	1.411	37
Crinoid sp.5	0.262	0.091	0.900	0.352	0.336	1.679	46
Astropecten granulatus	0.509	0.143	1.000	0.652	0.457	0.473	35
Astropecten sp.4	0.418	0.117	1.000	0.535	0.414	0.211	39
Metrodira subulata	0.531	0.140	1.028	0.671	0.464	0.148	34
Stellaster equestris	0.707	0.141	1.186	0.848	0.522	1.099	30
Laganum sp.3	0.849	0.238	1.000	1.087	0.590	0.829	26
Average			1.074		0.423		38

APPENDIX.3.B FULL SET OF SINGLE-SPECIES RESULTS FROM ANALYSIS OF COVARIANCE OF BYCATCH SPECIES

Table App.3.B.1 Significance level for log-transformed weight for bycatch species present in at least 11 tows.

Species	*f*	mud	carbonate	depth	habitat	Year	north vs south	closed vs open
Elasmobranchs								
Dasyatis leylandi	33	.887	.686	.750	.904	.366	.873	.734
Teleosts								
Acentrogobius caninus	16	.641	.560	.544	.111	< .001	.903	.670
Apistus carinatus	80	< .001	.454	.081	.246	.723	.781	.181
Apogon brevicaudatus	39	.935	.045	.007	.199	.159	.006	.528
Apogon ellioti	90	< .001	.047	.679	.160	.003	.468	.494
Apogon fasciatus	76	< .001	.109	.270	.068	.068	.888	.399
Apogon melanopus	11	.686	.025	.282	.767	.049	.765	.724
Apogon poecilopterus	23	.013	.009	.167	.766	< .001	< .001	.017
Apogon septemstriatus	35	.001	.009	.452	.916	< .001	.070	.986
Callionymus belcheri	11	.573	.284	.031	.024	.946	.019	.392
Callionymus grossi	75	.001	< .001	< .001	.274	.041	< .001	.633
Canthigaster compressa	16	< .001	.007	.022	.095	.836	.001	.969
Caranx bucculentus	14	.840	.644	.981	.275	.051	.067	.477
Centriscus scutatus	22	.891	.610	.335	.810	.946	.264	.279
Choerodon cephalotes	79	.061	.192	.030	.311	.726	.001	.686
Choerodon monostigma	15	.408	.138	.690	.637	.407	.010	.369
Choerodon sp.2	66	.029	.800	.119	.896	.109	.048	.138
Cymbacephalus nematophthalmus	12	.663	.045	.276	.309	.951	.578	.421
Dactyloptena papilio	38	.003	.003	.426	.838	.190	.918	.945
Dactylopus dactylopus	49	.127	.377	.032	.534	.067	.791	.519
Diagramma pictum	35	.003	.074	.002	.363	< .001	.449	.576
Engyprosopon grandisquama	87	.014	.001	.951	.761	.164	< .001	.060
Epinephelus sexfasciatus	23	.119	.207	.056	.754	.855	.191	.126
Euristhmus nudiceps	75	< .001	.456	.219	.020	.806	.003	.827
Fistularia petimba	60	< .001	.568	.362	.170	.008	.072	.977
Gerres oyena	32	.256	.049	.010	.521	.265	.596	.026
Grammatobothus polyophthalmus	41	.001	.648	.059	.656	.540	.711	.483
Lagocephalus sceleratus	71	.006	.992	.033	.109	< .001	.431	.060
Leiognathus moretoniensis	16	.568	.134	.007	.488	.089	.001	.174
Leiognathus sp.	49	< .001	.594	.111	.120	.065	.421	.057
Lepidotrigla argus	23	.366	.341	.001	.854	.907	.206	.123
Lethrinus genivittatus	111	.234	.376	.018	.350	.114	< .001	.009
Lutjanus vittus	13	.381	.745	.009	.530	.677	.643	.827
Monacanthus chinensis	12	.493	.168	.090	.226	.673	.119	.153
Nemipterus furcosus	113	< .001	.038	.102	.243	.163	.037	.721
Nemipterus hexodon	32	< .001	.384	.151	.016	.273	.007	.483
Nemipterus peronii	72	< .001	.011	.115	.812	.972	.967	.293
Paracentropogon longispinis	33	.013	.401	.634	.144	.166	.016	.171
Parachaetodon ocellatus	24	.013	.495	.218	.526	.259	.046	.396
Paramonacanthus choirocephalus	112	< .001	.019	.266	.623	.005	.012	.900
Paramonacanthus japonicus	102	.016	.392	.573	.813	.467	.001	.373

Species	***f***	**mud**	**carbonate**	**depth**	**habitat**	**Year**	**north vs south**	**closed vs open**
Parapercis nebulosa	13	.264	.451	.098	.021	.453	.493	.179
Pelates quadrilineatus	19	.018	.268	.517	.466	.453	.014	.181
Pentapodus paradiseus	76	.317	.658	.418	.193	.673	< .001	.293
Pentaprion longimanus	21	.002	.808	.141	.770	.065	.002	.422
Platax teira	11	.073	.881	.088	.689	.001	.520	.448
Priacanthus tayenus	77	< .001	.700	.398	.178	.020	.462	.981
Pristotis jerdoni	31	< .001	.489	.357	.205	.254	.450	.112
Pseudomonacanthus peroni	24	< .001	.014	.198	.734	.703	.117	.967
Pseudorhombus argus	48	.001	.069	.184	.205	.665	1.000	.844
Pseudorhombus diplospilus	67	< .001	.473	.087	.609	.201	.137	.989
Pseudorhombus dupliciocellatus	27	.029	.909	.002	.126	.001	.379	.630
Pseudorhombus elevatus	23	.222	.286	.357	.870	.868	.029	.074
Pseudorhombus jenynsii	12	.599	.749	.817	.453	.662	.447	.434
Pseudorhombus spinosus	86	.001	.189	.010	.785	.005	< .001	.986
Rhynchostracion nasus	73	< .001	.025	.322	.099	.717	.795	.441
Saurida micropectoralis	19	.763	.060	.002	.050	.305	.005	.873
Saurida undosquamis	112	.003	.258	.183	.225	.037	.864	.004
Scolopsis taeniopterus	88	< .001	.006	.052	.215	.919	.764	.919
Selaroides leptolepis	62	.001	.399	.808	.493	.132	.105	.451
Siganus canaliculatus	73	< .001	.112	.019	.393	.707	.111	.674
Sillago ingenuua	38	.004	.254	.178	.642	.050	.253	.210
Sillago maculata	26	.393	.020	.041	.766	.689	.031	.565
Siphamia argyrogaster	33	.040	.108	.840	.308	.040	.182	.763
Sorsogona tuberculata	90	.007	.006	.172	.649	.037	.080	.161
Suggrundus isacanthus	86	< .001	.021	.660	.445	.859	.009	.300
Synchiropus rameus	35	.001	.359	.145	.870	.313	.015	.442
Synodus hoshinonis	22	.659	.087	.259	.780	.756	.022	.005
Synodus sageneus	52	.221	.415	.413	.272	.356	.100	.423
Terapon theraps	12	.009	.090	.430	.808	.011	.005	.489
Torquigener pallimaculatus	87	.015	.200	.257	.081	.050	.198	.289
Torquigener whitleyi	12	.113	.121	< .001	.630	.141	.954	.174
Trachinocephalus myops	27	< .001	.012	.970	.732	.244	.746	.476
Tragulichthys jaculiferus	27	.002	.825	.868	.430	.414	.455	.274
Upeneus asymmetricus	55	.034	.685	.372	.838	.304	.751	.407
Upeneus luzonius	56	.027	.255	.001	.631	.146	.097	.027
Upeneus sundaicus	36	.055	.103	< .001	.826	.225	< .001	.882
Upeneus tragula	90	< .001	.013	.861	.050	.221	< .001	.016
Yongeichthys nebulosus	18	.029	.047	.379	.064	< .001	.096	.922
Algae								
Algae	15	< .001	.340	.315	.472	.289	.032	.402
Sponges								
Porifera	51	.272	.045	.020	.617	.104	.012	.002
Cnidarians								
Alcyonacea	22	.061	.494	.885	.046	< .001	.215	.871
Gorgonacea	44	.726	.773	.014	.751	.644	.399	.626
Hydroid: Hydrozoa	15	.029	.117	.008	.131	< .001	.752	.006
Hydrozoa	11	.673	.307	.153	.057	.008	.960	.587
Scleractinia	13	.086	.311	.367	.927	.150	.975	.400
Soft corals	27	.170	.195	.533	.417	< .001	.181	.438
Crustaceans								
Charybdis jaubertensis	12	.084	.765	.890	.143	.168	.874	.831
Charybdis truncata	36	.199	.978	.725	.282	.420	.201	.484
Lupocyclus rotundatus	11	.587	.970	.619	.466	.621	.694	.078
Metapenaeopsis palmensis	51	.652	.316	.198	.422	< .001	.006	.815
Metapenaeopsis sp.	25	.116	.200	.194	.126	< .001	.792	.186

Species	***f***	**mud**	**carbonate**	**depth**	**habitat**	**Year**	**north vs south**	**closed vs open**
Metapenaeus endeavouri	14	.025	.199	.232	.347	.876	.086	.804
Portunus gracilimanus	27	< .001	.192	.694	.493	.096	.063	.179
Portunus pelagicus	40	.621	.072	< .001	.628	.794	.714	.529
Portunus rubromarginatus	109	.126	.732	.485	.207	.546	.163	.034
Portunus tenuipes	107	.006	.119	.670	.623	.320	.030	.381
Scyllaridae	34	.302	< .001	.641	.724	< .001	.974	.892
Scyllarus sp.2	15	.092	< .001	.080	.504	< .001	.451	.532
Thenus maculata	33	.002	.161	.105	.156	.357	.754	.456
Thenus orientalis	69	< .001	.210	.364	.742	.091	.035	.808
Trachypenaeus anchoralis	11	.314	.002	.567	.441	.001	.033	.240
Trachypenaeus granulosus	44	< .001	.517	.113	.769	.125	.193	.764
Trachypenaeus sp.	11	.992	.513	.056	.346	< .001	.929	.164
Molluscs								
Amusiidae	79	< .001	.001	.678	.100	< .001	.194	.195
Annachlamys flabellata	37	< .001	.002	< .001	.010	.051	.822	.381
Bivalvia	18	.020	.050	.026	.498	.027	.114	.464
Octopoda	21	.011	.128	.123	.613	.756	.484	.069
Sepioidae	90	.033	.582	.046	.264	.845	.341	.405
Teuthoidea	40	.408	.215	.051	.892	.023	.602	.923
Echinoderms								
Asteroid (mixed spp.)	28	.002	.532	.012	.099	.786	.194	.170
Crinoidea	40	< .001	.014	.817	.188	.623	.669	.341
Gorgonocephalidae	16	.115	.137	.844	.423	.153	.385	.998
Holothurioidea	24	.111	.941	.921	.757	.775	.419	.108
Laganidae	21	.141	.580	.005	.131	.606	.474	.298
Spatangoida	11	.023	.984	.987	.510	.364	.423	.689
Ascidians								
Ascidiacea (mixed spp.)	14	.134	.104	.325	.523	.347	.265	.205

Table App.3.B.2 Estimated coefficient for log-transformed weight for bycatch species present in at least 11 tows.

Species	mud	carbonate	depth	habitat	year	north vs south	closed vs open
Elasmobranchs							
Dasyatis leylandi	0.028	0.098	–0.077	0.015	–0.086	0.012	–0.032
Teleosts							
Acentrogobius caninus	0.054	–0.083	–0.085	0.119	–0.264	0.005	0.023
Apistus carinatus	1.427	–0.200	0.465	0.162	–0.037	–0.022	–0.138
Apogon brevicaudatus	–0.015	–0.460	–0.618	0.153	0.126	0.192	0.055
Apogon ellioti	2.632	–0.664	–0.136	0.245	0.394	–0.072	–0.087
Apogon fasciatus	2.903	–0.609	–0.415	0.362	0.273	–0.016	0.122
Apogon melanopus	0.051	–0.348	–0.165	0.024	0.120	0.014	–0.021
Apogon poecilopterus	0.471	–0.607	–0.315	0.036	0.395	–0.304	–0.214
Apogon septemstriatus	0.638	–0.593	0.166	–0.012	0.394	0.121	–0.001
Callionymus belcheri	–0.055	–0.128	–0.257	–0.141	–0.003	–0.084	–0.039
Callionymus grossi	0.705	–1.157	–0.972	–0.146	0.206	0.311	0.047
Canthigaster compressa	–0.788	0.517	–0.435	0.167	0.015	–0.197	–0.003
Caranx bucculentus	0.022	–0.062	0.003	–0.076	–0.103	–0.074	–0.036
Centriscus scutatus	–0.028	0.126	0.237	0.031	0.007	0.083	–0.103
Choerodon cephalotes	0.483	–0.411	–0.682	0.166	–0.043	0.322	0.049
Choerodon monostigma	0.119	–0.261	0.069	–0.043	–0.057	–0.138	–0.060
Choerodon sp.2	0.630	0.088	0.542	–0.024	–0.221	0.209	–0.199
Cymbacephalus nematophthalmus	0.038	0.212	–0.114	–0.056	0.003	0.018	–0.033
Dactyloptena papilio	0.693	–0.823	0.217	–0.029	0.142	0.008	0.007
Dactylopus dactylopus	0.329	0.232	–0.565	0.085	0.190	0.021	–0.065
Diagramma pictum	0.652	–0.478	–0.843	0.126	0.570	–0.060	0.057
Engyprosopon grandisquama	0.604	–1.013	0.018	–0.047	0.164	0.524	–0.217
Epinephelus sexfasciatus	0.249	–0.246	–0.372	0.032	–0.014	–0.076	0.115
Euristhmus nudiceps	2.165	–0.200	–0.328	0.330	–0.026	0.244	–0.022
Fistularia petimba	1.706	–0.170	0.270	0.214	0.316	0.162	0.003
Gerres oyena	0.190	–0.405	–0.528	–0.068	–0.090	0.032	0.177
Grammatobothus polyophthalmus	0.659	0.106	0.441	–0.054	–0.056	–0.026	0.063
Lagocephalus sceleratus	0.504	0.002	–0.471	0.185	–0.370	0.052	–0.160
Leiognathus moretoniensis	0.094	–0.304	–0.554	–0.073	0.136	–0.204	–0.106
Leiognathus sp.	1.265	–0.227	–0.678	0.348	–0.312	0.103	0.314
Lepidotrigla argus	0.141	–0.181	0.625	–0.018	–0.009	–0.072	–0.113
Lethrinus genivittatus	0.346	0.314	–0.842	0.173	–0.221	0.428	0.363
Lutjanus vittus	–0.088	–0.040	–0.321	–0.040	0.020	0.017	–0.010
Monacanthus chinensis	0.086	–0.212	–0.259	0.097	0.025	0.072	0.084
Nemipterus furcosus	1.567	–0.536	0.418	0.156	–0.141	0.161	0.035
Nemipterus hexodon	0.982	0.231	–0.380	–0.339	–0.115	–0.218	0.071
Nemipterus peronii	1.984	–0.722	–0.440	–0.035	–0.004	–0.003	0.113
Paracentropogon longispinis	–0.518	–0.212	–0.119	–0.193	0.138	0.184	–0.133
Parachaetodon ocellatus	0.421	–0.139	–0.250	0.068	0.091	0.123	0.066
Paramonacanthus choirocephalus	1.134	–0.734	–0.343	0.080	0.350	0.236	–0.015
Paramonacanthus japonicus	0.592	–0.255	0.166	–0.037	–0.085	0.296	0.102
Parapercis nebulosa	–0.128	–0.106	0.232	–0.172	0.041	0.029	–0.073
Pelates quadrilineatus	0.420	–0.239	0.138	–0.082	0.064	–0.160	–0.111
Pentapodus paradiseus	–0.312	0.168	0.306	0.260	0.063	0.624	0.154
Pentaprion longimanus	0.498	0.047	–0.286	–0.030	0.143	–0.186	–0.060
Platax teira	0.310	–0.032	–0.359	–0.044	0.273	0.041	0.061
Priacanthus tayenus	2.697	0.116	0.252	0.212	–0.278	–0.066	–0.003
Pristotis jerdoni	–1.144	0.251	–0.332	0.241	0.163	0.082	0.222

Species	**mud**	**carbonate**	**depth**	**habitat**	**year**	**north vs south**	**closed vs open**
Pseudomonacanthus peroni	0.611	0.518	–0.267	–0.037	–0.031	0.098	0.003
Pseudorhombus argus	–0.897	0.565	–0.408	–0.205	–0.053	0.000	–0.023
Pseudorhombus diplospilus	1.220	–0.205	–0.489	0.076	0.144	0.128	0.001
Pseudorhombus dupliciocellatus	0.368	0.023	0.638	0.164	0.280	–0.054	–0.038
Pseudorhombus elevatus	0.175	–0.187	–0.160	–0.015	0.011	–0.115	–0.121
Pseudorhombus jenynsii	–0.053	–0.040	0.028	0.048	–0.021	0.028	–0.037
Pseudorhombus spinosus	1.082	–0.496	–0.979	–0.054	0.420	0.435	–0.002
Rhynchostracion nasus	2.084	–0.976	0.423	0.372	–0.061	–0.034	0.127
Saurida micropectoralis	0.056	0.429	–0.707	–0.234	–0.091	–0.193	–0.014
Saurida undosquamis	0.693	0.318	–0.372	–0.178	0.232	0.014	–0.312
Scolopsis taeniopterus	2.917	–0.767	–0.539	0.180	–0.011	0.025	0.011
Selaroides leptolepis	1.129	–0.342	0.098	0.145	–0.241	–0.198	–0.117
Siganus canaliculatus	1.847	–0.599	–0.886	0.168	0.055	0.180	0.061
Sillago ingenuua	–0.664	–0.316	–0.371	–0.067	–0.215	–0.095	–0.133
Sillago maculata	0.114	–0.386	–0.334	0.025	0.026	–0.107	0.036
Siphamia argyrogaster	–0.406	0.386	–0.048	–0.128	0.194	–0.096	0.028
Sorsogona tuberculata	1.044	1.312	0.638	0.111	–0.389	0.248	–0.253
Suggrundus isacanthus	1.198	–0.453	–0.085	0.077	–0.014	–0.153	–0.077
Synchiropus rameus	0.652	–0.210	0.331	–0.019	0.091	–0.168	–0.067
Synodus hoshinonis	–0.083	0.396	0.258	–0.034	0.028	0.160	–0.254
Synodus sageneus	0.248	–0.202	–0.201	0.142	0.090	0.123	–0.076
Terapon theraps	0.352	0.277	–0.128	0.021	–0.166	–0.139	–0.043
Torquigener pallimaculatus	0.695	0.442	–0.388	–0.316	–0.268	–0.133	–0.140
Torquigener whitleyi	–0.143	–0.171	–0.486	–0.028	–0.064	0.002	0.058
Trachinocephalus myops	–1.024	0.533	–0.008	0.037	0.096	–0.020	–0.057
Tragulichthys jaculiferus	0.659	–0.057	0.042	–0.106	–0.083	0.058	–0.109
Upeneus asymmetricus	0.721	–0.167	–0.366	–0.044	0.167	–0.039	0.131
Upeneus luzonius	–0.466	–0.290	–0.832	0.064	0.146	0.127	0.219
Upeneus sundaicus	0.342	–0.356	–1.016	–0.025	0.104	–0.300	–0.012
Upeneus tragula	1.710	–0.926	0.064	0.381	–0.178	0.421	0.345
Yongeichthys nebulosus	0.498	–0.554	0.241	0.269	0.488	–0.139	–0.010
Algae							
Algae	–0.860	0.213	0.222	–0.084	0.093	–0.145	0.072
Sponges							
Porifera	0.678	–1.523	–1.764	0.197	0.484	0.572	0.932
Cnidarians							
Alcyonacea	–0.334	–0.148	0.031	0.227	–0.579	0.080	0.013
Gorgonacea	–0.142	–0.143	–1.230	–0.082	–0.090	–0.125	–0.092
Hydroid: Hydrozoa	–0.415	–0.362	–0.613	0.182	–0.468	0.022	0.249
Hydrozoa	0.060	–0.179	0.249	0.176	0.184	0.003	0.037
Scleractinia	–0.455	0.327	–0.289	–0.015	0.183	–0.003	0.104
Soft corals	–0.406	0.468	0.223	–0.153	0.529	0.145	0.107
Crustaceans							
Charybdis jaubertensis	0.229	0.048	0.022	–0.124	0.088	–0.008	–0.013
Charybdis truncata	0.383	–0.010	–0.127	–0.205	0.115	–0.140	–0.098
Lupocyclus rotundatus	0.060	0.005	–0.066	–0.051	–0.026	0.016	0.091
Metapenaeopsis palmensis	–0.097	0.265	–0.338	–0.111	0.622	0.219	–0.024
Metapenaeopsis sp.	0.216	–0.215	0.216	–0.134	–0.462	0.013	–0.085
Metapenaeus endeavouri	0.271	0.188	–0.174	–0.072	–0.009	–0.076	–0.014
Portunus gracilimanus	0.792	–0.331	0.099	0.091	0.166	–0.142	–0.131
Portunus pelagicus	–0.134	–0.599	–1.296	0.084	0.034	0.036	0.080
Portunus rubromarginatus	0.410	–0.112	–0.227	–0.216	0.078	0.137	–0.268
Portunus tenuipes	0.924	–0.632	–0.170	–0.104	0.158	0.264	–0.136
Scyllaridae	0.146	–0.664	–0.080	–0.032	0.370	0.002	–0.009
Scyllarus sp.2	–0.207	–0.603	0.262	–0.052	–0.291	–0.034	–0.036

Species	**mud**	**carbonate**	**depth**	**habitat**	**year**	**north vs south**	**closed vs open**
Thenus maculata	−1.086	0.585	0.673	−0.309	0.151	−0.039	0.119
Thenus orientalis	1.342	−0.478	−0.343	0.065	−0.254	−0.243	0.035
Trachypenaeus anchoralis	0.141	−0.536	0.098	−0.069	0.227	0.110	−0.078
Trachypenaeus granulosus	1.105	0.181	0.441	−0.043	−0.169	0.109	−0.032
Trachypenaeus sp.	0.001	−0.098	0.286	0.074	−0.246	0.004	−0.080
Molluscs							
Amusiidae	2.734	−1.007	−0.125	0.262	0.479	−0.118	−0.151
Annachlamys flabellata	1.023	−0.781	0.865	0.332	0.186	−0.016	0.081
Bivalvia	0.429	0.439	−0.497	−0.079	0.196	0.106	0.063
Octopoda	−0.589	0.426	0.428	0.074	0.034	0.058	0.196
Sepioidae	0.763	−0.239	−0.867	−0.254	0.033	0.124	−0.139
Teuthoidea	−0.236	0.433	−0.681	0.025	0.315	−0.054	0.013
Echinoderms							
Asteroid (mixed spp.)	−1.292	0.307	−1.246	−0.426	−0.052	−0.192	0.259
Crinoidea	−1.708	0.860	0.080	−0.239	−0.067	−0.044	0.127
Gorgonocephalidae	−0.339	0.392	−0.051	−0.110	0.148	0.068	0.000
Holothurioidea	−0.623	0.035	−0.047	0.077	−0.053	0.115	0.294
Laganidae	0.319	0.146	−0.750	0.209	0.054	−0.057	0.106
Spatangoida	0.400	−0.004	0.003	0.073	−0.076	−0.051	−0.033
Ascidians							
Ascidiacea (mixed spp.)	−0.288	0.382	−0.229	−0.078	−0.086	0.078	−0.114

Table App.3.B.3 Significance level for log-transformed number for bycatch species present in at least 11 tows.

Species	*f*	mud	carbonate	depth	habitat	year	north vs south	closed vs open
Elasmobranchs								
Dasyatis leylandi	33	.739	.867	.900	.901	.290	.904	.926
Teleosts								
Acentrogobius caninus	16	.745	.349	.487	.067	< .001	.620	.489
Apistus carinatus	80	< .001	.364	.119	.220	.756	.848	.144
Apogon brevicaudatus	39	.760	.018	.002	.430	.102	.003	.428
Apogon ellioti	90	< .001	.034	.381	.311	< .001	.373	.784
Apogon fasciatus	76	< .001	.031	.177	.116	< .001	.527	.764
Apogon melanopus	11	.634	.035	.160	.928	.027	.865	.712
Apogon poecilopterus	23	.024	.005	.099	.827	< .001	< .001	.007
Apogon septemstriatus	35	< .001	.018	.489	.681	< .001	.061	.714
Callionymus belcheri	11	.550	.365	.013	.019	.871	.022	.452
Callionymus grossi	75	.010	< .001	< .001	.253	.033	< .001	.511
Canthigaster compressa	16	< .001	.007	.019	.089	.910	< .001	.819
Caranx bucculentus	14	.960	.711	.839	.046	.011	.006	.264
Centriscus scutatus	22	.830	.422	.551	.697	.747	.319	.447
Choerodon cephalotes	79	.085	.044	.021	.424	.849	< .001	.967
Choerodon monostigma	15	.563	.076	.598	.664	.227	.009	.492
Choerodon sp.2	66	.114	.962	.070	.989	.298	.014	.303
Cymbacephalus nematophthalmus	12	.670	.055	.424	.341	.977	.549	.444
Dactyloptena papilio	38	.001	< .001	.401	.752	.068	.720	.919
Dactylopus dactylopus	49	.203	.684	.018	.623	.013	.897	.550
Diagramma pictum	35	.006	.039	.001	.772	< .001	.451	.580
Engyprosopon grandisquama	87	.047	.001	.719	.713	.129	< .001	.020
Epinephelus sexfasciatus	23	.393	.092	.008	.547	.866	.149	.143
Euristhmus nudiceps	75	< .001	.284	.260	.023	.875	.001	.774
Fistularia petimba	60	< .001	.726	.863	.254	.002	.113	.797
Gerres oyena	32	.477	.036	.001	.319	.273	.617	.009
Grammatobothus polyophthalmus	41	< .001	.754	.091	.670	.469	.604	.522
Lagocephalus sceleratus	71	.018	.864	.016	.135	< .001	.477	.104
Leiognathus moretoniensis	16	.887	.116	.003	.481	.122	.002	.218
Leiognathus sp.	49	.005	.374	.022	.157	.171	.729	.017
Lepidotrigla argus	23	.400	.299	.001	.798	.874	.168	.108
Lethrinus genivittatus	111	.274	.562	.003	.494	.352	< .001	.004
Lutjanus vittus	13	.480	.820	.002	.272	.401	.886	.928
Monacanthus chinensis	12	.543	.270	.033	.237	.558	.161	.120
Nemipterus furcosus	113	< .001	.012	.236	.479	.180	.002	.713
Nemipterus hexodon	32	< .001	.856	.143	.024	.443	.014	.573
Nemipterus peronii	72	< .001	.001	.010	.822	.042	.500	.446
Paracentropogon longispinis	33	.012	.574	.498	.262	.186	.021	.168
Parachaetodon ocellatus	24	.020	.238	.158	.448	.096	.028	.460
Paramonacanthus choirocephalus	112	< .001	.003	.053	.581	< .001	.042	.705
Paramonacanthus japonicus	102	.005	.253	.969	.859	.776	.002	.557
Parapercis nebulosa	13	.310	.489	.115	.026	.476	.391	.091
Pelates quadrilineatus	19	.030	.228	.621	.401	.343	.012	.203
Pentapodus paradiseus	76	.403	.849	.981	.273	.527	< .001	.370
Pentaprion longimanus	21	.006	.947	.031	.573	.015	.001	.211
Platax teira	11	.036	.739	.061	.589	.003	.551	.432
Priacanthus tayenus	77	< .001	.388	.941	.246	.091	.259	.658
Pristotis jerdoni	31	< .001	.357	.260	.153	.269	.609	.130
Pseudomonacanthus peroni	24	< .001	.011	.154	.396	.675	.140	.953

Species	*f*	mud	carbon ate	depth	habitat	year	north vs south	closed vs open
Pseudorhombus argus	48	.001	.084	.196	.262	.954	.951	.894
Pseudorhombus diplospilus	67	< .001	.199	.117	.562	.020	.026	.799
Pseudorhombus dupliciocellatus	27	.015	.880	.005	.078	< .001	.550	.762
Pseudorhombus elevatus	23	.256	.228	.431	.728	.922	.019	.055
Pseudorhombus jenynsii	12	.687	.680	.851	.507	.964	.425	.346
Pseudorhombus spinosus	86	.001	.035	.010	.871	< .001	< .001	.864
Rhynchostracion nasus	73	< .001	.002	.727	.318	.166	.622	.034
Saurida micropectoralis	19	.744	.157	.001	.075	.703	.030	.489
Saurida undosquamis	112	< .001	.713	.163	.379	.006	.214	.003
Scolopsis taeniopterus	88	< .001	.001	.001	.702	.235	.681	.891
Selaroides leptolepis	62	.001	.520	.795	.543	.236	.047	.470
Siganus canaliculatus	73	< .001	.100	.003	.467	.091	.088	.671
Sillago ingenuua	38	.004	.188	.105	.532	.036	.199	.229
Sillago maculata	26	.566	.013	.014	.887	.842	.030	.527
Siphamia argyrogaster	33	.078	.127	.915	.354	.023	.146	.896
Sorsogona tuberculata	90	.128	.002	.283	.935	.057	.043	.047
Suggrundus isacanthus	86	< .001	.004	.130	.387	.776	.004	.172
Synchiropus rameus	35	.001	.262	.148	.862	.233	.012	.350
Synodus hoshinonis	22	.529	.087	.236	.776	.734	.019	.003
Synodus sageneus	52	.308	.488	.269	.308	.217	.042	.245
Terapon theraps	12	.019	.274	.275	.853	.026	.009	.646
Torquigener pallimaculatus	87	.013	.528	.105	.113	.028	.250	.359
Torquigener whitleyi	12	.104	.133	< .001	.495	.156	.899	.151
Trachinocephalus myops	27	< .001	.016	.927	.812	.331	.888	.245
Tragulichthys jaculiferus	27	.001	.676	.873	.206	.211	.138	.348
Upeneus asymmetricus	55	.062	.674	.227	.741	.164	.865	.535
Upeneus luzonius	56	.054	.225	< .001	.658	.040	.064	.020
Upeneus sundaicus	36	.163	.066	< .001	.654	.137	< .001	.965
Upeneus tragula	90	< .001	.005	.668	.047	.197	< .001	.008
Yongeichthys nebulosus	18	.040	.051	.522	.103	< .001	.113	.958
Algae								
Algae	15	< .001	.062	.875	.297	.208	.068	.758
Sponges								
Porifera	51	.449	.230	.059	.327	.105	.125	.002
Cnidarians								
Alcyonacea	22	.027	.491	.898	.097	< .001	.225	.475
Gorgonacea	44	.936	.662	.002	.713	.806	.381	.876
Hydroid: Hydrozoa	15	.041	.284	.052	.496	< .001	.488	.044
Hydrozoa	11	.735	.445	.065	.154	.014	.916	.328
Scleractinia	13	.047	.032	.034	.850	.119	.531	.678
Soft corals	27	.353	.132	.808	.713	< .001	.259	.743
Crustaceans								
Charybdis jaubertensis	12	.080	.896	.926	.168	.191	.831	.877
Charybdis truncata	36	.151	.944	.781	.535	.179	.280	.515
Lupocyclus rotundatus	11	.967	.835	.612	.748	.818	.557	.058
Metapenaeopsis palmensis	51	.915	.249	.216	.501	< .001	.009	.608
Metapenaeopsis sp.	25	.068	.452	.200	.131	< .001	.875	.190
Metapenaeus endeavouri	14	.038	.207	.205	.252	.847	.072	.860
Portunus gracilimanus	27	< .001	.170	.615	.540	.091	.072	.211
Portunus pelagicus	40	.910	.006	< .001	.476	.616	.717	.554
Portunus rubromarginatus	109	.124	.479	.691	.181	.291	.272	.015
Portunus tenuipes	107	.016	.138	.757	.682	.325	.033	.353
Scyllaridae	34	.224	< .001	.761	.716	< .001	.874	.942
Scyllarus sp.2	15	.084	< .001	.044	.520	< .001	.378	.453
Thenus maculata	33	.013	.365	.042	.128	.705	.742	.319

Species	***f***	**mud**	**carbon ate**	**depth**	**habitat**	**year**	**north vs south**	**closed vs open**
Thenus orientalis	69	< .001	.339	.183	.424	.114	.092	.134
Trachypenaeus anchoralis	11	.259	.003	.622	.393	.001	.023	.332
Trachypenaeus granulosus	44	< .001	.290	.250	.751	.038	.226	.729
Trachypenaeus sp.	11	.636	.597	.079	.321	< .001	.983	.318
Molluscs								
Amusiidae	79	< .001	.001	.851	.100	< .001	.107	.087
Annachlamys flabellata	37	< .001	.001	< .001	.035	.048	.761	.549
Bivalvia	18	.119	.043	.017	.856	.119	.198	.243
Octopoda	21	.003	.226	.047	.999	.976	.559	.135
Sepioidae	90	.018	.556	.004	.264	.621	.321	.434
Teuthoidea	40	.110	.350	.014	.885	.015	.572	.481
Echinoderms								
Asteroid (mixed spp.)	28	< .001	.523	.041	.140	.872	.061	.148
Crinoidea	40	< .001	.060	.787	.302	.967	.205	.270
Gorgonocephalidae	16	.197	.111	.874	.680	.075	.552	.693
Holothurioidea	24	.268	.857	.882	.855	.482	.477	.127
Laganidae	21	.110	.497	.018	.195	.758	.288	.771
Spatangoida	11	.028	.949	.995	.532	.464	.335	.958
Ascidians								
Ascidiacea (mixed spp.)	14	.181	.055	.295	.305	.720	.286	.061

Table App.3.B.4 Estimated coefficient for log-transformed number for bycatch species present in at least 11 tows.

Species	mud	carbonate	depth	habitat	year	north vs south	closed vs open
Elasmobranchs							
Dasyatis leylandi	0.036	0.022	0.017	0.009	–0.055	0.005	0.005
Teleosts							
Acentrogobius caninus	0.029	–0.104	–0.076	0.107	–0.205	0.016	0.029
Apistus carinatus	1.296	–0.227	0.388	0.161	0.031	–0.014	–0.141
Apogon brevicaudatus	–0.037	–0.356	–0.465	0.061	0.096	0.135	0.045
Apogon ellioti	1.455	–0.509	–0.207	0.126	0.343	–0.063	–0.025
Apogon fasciatus	1.696	–0.498	–0.308	0.189	0.366	–0.043	–0.026
Apogon melanopus	0.050	–0.274	–0.180	0.006	0.113	0.007	–0.018
Apogon poecilopterus	0.274	–0.420	–0.242	0.017	0.241	–0.202	–0.155
Apogon septemstriatus	0.435	–0.332	0.095	–0.030	0.289	0.079	–0.020
Callionymus belcheri	–0.054	–0.099	–0.274	–0.136	0.007	–0.076	–0.032
Callionymus grossi	0.433	–1.056	–0.890	–0.121	0.170	0.226	0.051
Canthigaster compressa	–0.749	0.515	–0.439	0.167	0.008	–0.203	–0.016
Caranx bucculentus	–0.004	–0.035	–0.019	–0.100	–0.097	–0.079	–0.041
Centriscus scutatus	0.023	0.105	0.077	0.027	–0.017	0.039	–0.038
Choerodon cephalotes	0.344	–0.493	–0.563	0.102	–0.018	0.277	–0.004
Choerodon monostigma	0.046	–0.174	0.051	–0.022	–0.046	–0.078	–0.026
Choerodon sp.2	0.275	0.010	0.384	–0.002	–0.087	0.158	–0.084
Cymbacephalus nematophthalmus	0.030	0.168	–0.069	–0.043	–0.001	0.016	–0.026
Dactyloptena papilio	0.542	–0.689	0.157	–0.031	0.136	0.020	0.007
Dactylopus dactylopus	0.187	0.073	–0.425	0.046	0.178	–0.007	–0.041
Diagramma pictum	0.419	–0.384	–0.602	0.028	0.391	–0.042	0.039
Engyprosopon grandisquama	0.395	–0.826	–0.086	–0.046	0.145	0.421	–0.217
Epinephelus sexfasciatus	0.084	–0.204	–0.321	0.038	–0.008	–0.052	0.068
Euristhmus nudiceps	1.749	–0.243	–0.253	0.271	–0.014	0.226	–0.025
Fistularia petimba	1.224	–0.071	0.035	0.121	0.246	0.097	–0.020
Gerres oyena	0.102	–0.374	–0.578	–0.092	–0.076	0.026	0.178
Grammatobothus polyophthalmus	0.516	0.052	0.279	–0.037	–0.047	–0.026	0.041
Lagocephalus sceleratus	0.348	–0.030	–0.429	0.139	–0.325	0.038	–0.111
Leiognathus moretoniensis	0.019	–0.257	–0.490	–0.060	0.099	–0.153	–0.077
Leiognathus sp.	0.645	–0.245	–0.633	0.204	–0.148	0.028	0.254
Lepidotrigla argus	0.123	–0.187	0.589	–0.024	–0.011	–0.074	–0.111
Lethrinus genivittatus	0.291	0.188	–0.964	0.116	–0.119	0.471	0.363
Lutjanus vittus	–0.057	–0.023	–0.318	–0.057	0.033	0.004	0.003
Monacanthus chinensis	0.044	–0.097	–0.188	0.054	0.020	0.037	0.053
Nemipterus furcosus	1.336	–0.581	0.269	0.084	–0.120	0.213	–0.032
Nemipterus hexodon	0.614	–0.032	–0.259	–0.211	0.054	–0.132	0.038
Nemipterus peronii	1.293	–0.721	–0.543	–0.025	0.170	–0.043	0.062
Paracentropogon longispinis	–0.434	–0.117	–0.141	–0.123	0.109	0.146	–0.111
Parachaetodon ocellatus	0.232	–0.142	–0.169	0.048	0.079	0.080	0.034
Paramonacanthus choirocephalus	1.010	–0.792	–0.515	0.077	0.418	0.163	–0.039
Paramonacanthus japonicus	0.572	–0.278	–0.009	–0.022	–0.027	0.233	0.055
Parapercis nebulosa	–0.097	–0.081	0.183	–0.137	0.033	0.030	–0.076
Pelates quadrilineatus	0.393	–0.265	0.108	–0.096	0.082	–0.167	–0.107
Pentapodus paradiseus	–0.224	0.063	–0.008	0.188	0.082	0.549	0.113
Pentaprion longimanus	0.384	0.011	–0.364	–0.050	0.162	–0.176	–0.081
Platax teira	0.130	0.025	–0.141	–0.021	0.089	0.013	0.023
Priacanthus tayenus	1.653	0.161	–0.014	0.113	–0.125	–0.063	–0.032
Pristotis jerdoni	–0.824	0.233	–0.284	0.190	0.110	0.039	0.148

Species	**mud**	**carbonate**	**depth**	**habitat**	**year**	**north vs south**	**closed vs open**
Pseudomonacanthus peroni	0.381	0.324	–0.178	–0.056	–0.021	0.056	–0.003
Pseudorhombus argus	–0.632	0.393	–0.291	–0.133	–0.005	0.004	–0.012
Pseudorhombus diplospilus	0.923	–0.243	–0.294	0.057	0.175	0.127	–0.018
Pseudorhombus dupliciocellatus	0.340	0.025	0.478	0.156	0.250	–0.030	–0.020
Pseudorhombus elevatus	0.129	–0.168	–0.109	–0.025	0.005	–0.099	–0.103
Pseudorhombus jenynsii	–0.031	–0.039	0.018	0.033	–0.002	0.023	–0.034
Pseudorhombus spinosus	0.635	–0.465	–0.571	–0.019	0.382	0.274	–0.014
Rhynchostracion nasus	0.987	–0.756	–0.085	0.127	–0.134	0.036	0.200
Saurida micropectoralis	–0.037	0.196	–0.468	–0.129	–0.021	–0.091	0.037
Saurida undosquamis	0.635	0.078	–0.295	–0.098	0.235	–0.079	–0.250
Scolopsis taeniopterus	2.247	–0.834	–0.816	0.050	0.118	0.031	0.013
Selaroides leptolepis	0.600	–0.146	–0.058	0.072	–0.106	–0.136	–0.063
Siganus canaliculatus	0.996	–0.384	–0.704	0.088	0.156	0.119	0.038
Sillago ingenuua	–0.573	–0.312	–0.383	–0.077	–0.196	–0.091	–0.109
Sillago maculata	0.072	–0.384	–0.377	0.011	0.012	–0.100	0.037
Siphamia argyrogaster	–0.248	0.262	0.018	–0.083	0.155	–0.075	0.009
Sorsogona tuberculata	0.310	0.771	0.265	0.011	–0.187	0.152	–0.191
Suggrundus isacanthus	1.043	–0.515	–0.268	0.080	0.020	–0.155	–0.093
Synchiropus rameus	0.537	–0.226	0.289	–0.018	0.094	–0.153	–0.072
Synodus hoshinonis	–0.085	0.283	0.194	–0.024	0.022	0.117	–0.188
Synodus sageneus	0.166	–0.138	–0.219	0.106	0.097	0.122	–0.089
Terapon theraps	0.147	0.083	–0.082	0.007	–0.067	–0.060	–0.013
Torquigener pallimaculatus	0.548	0.169	–0.432	–0.222	–0.233	–0.092	–0.094
Torquigener whitleyi	–0.166	–0.187	–0.577	–0.044	–0.069	0.005	0.069
Trachinocephalus myops	–0.679	0.369	–0.014	0.019	0.058	–0.006	–0.068
Tragulichthys jaculiferus	0.376	0.056	0.021	–0.090	–0.067	0.060	–0.049
Upeneus asymmetricus	0.555	–0.152	–0.434	–0.062	0.198	–0.018	0.086
Upeneus luzonius	–0.371	–0.285	–0.914	0.054	0.191	0.131	0.211
Upeneus sundaicus	0.240	–0.389	–1.106	–0.049	0.123	–0.282	–0.004
Upeneus tragula	1.236	–0.860	–0.129	0.317	–0.154	0.381	0.310
Yongeichthys nebulosus	0.264	–0.307	0.099	0.133	0.273	–0.074	0.003
Algae							
Algae	–0.291	0.158	–0.013	–0.046	0.042	–0.046	–0.010
Sponges							
Porifera	0.108	–0.209	–0.329	0.089	0.111	0.080	0.214
Cnidarians							
Alcyonacea	–0.179	–0.068	0.013	0.086	–0.270	0.036	0.027
Gorgonacea	0.010	0.065	–0.460	–0.029	–0.014	–0.039	–0.009
Hydroid: Hydrozoa	–0.128	–0.082	–0.148	0.027	–0.160	0.016	0.059
Hydrozoa	–0.022	–0.061	0.148	0.060	0.079	–0.003	0.030
Scleractinia	–0.170	0.225	–0.220	0.010	0.064	–0.020	–0.017
Soft corals	–0.109	0.217	0.035	–0.028	0.237	0.049	0.018
Crustaceans							
Charybdis jaubertensis	0.127	0.012	0.008	–0.064	0.046	–0.006	–0.005
Charybdis truncata	0.189	–0.011	–0.044	–0.052	0.085	–0.052	–0.040
Lupocyclus rotundatus	–0.003	–0.018	–0.045	–0.015	–0.008	0.016	0.065
Metapenaeopsis palmensis	0.018	0.242	–0.258	–0.074	0.454	0.166	–0.041
Metapenaeopsis sp.	0.231	–0.116	0.196	–0.122	–0.433	0.007	–0.077
Metapenaeus endeavouri	0.186	0.137	–0.137	–0.065	–0.008	–0.059	–0.007
Portunus gracilimanus	0.440	–0.185	0.067	0.043	0.090	–0.073	–0.065
Portunus pelagicus	–0.013	–0.410	–0.593	0.054	0.029	0.016	0.033
Portunus rubromarginatus	0.380	–0.213	–0.119	–0.211	0.125	0.099	–0.285
Portunus tenuipes	0.744	–0.556	–0.115	–0.080	0.145	0.241	–0.133
Scyllaridae	0.164	–0.682	–0.050	–0.031	0.358	–0.008	0.005
Scyllarus sp.2	–0.170	–0.509	0.241	–0.040	–0.232	–0.032	–0.034

Species	mud	carbonate	depth	habitat	year	north vs south	closed vs open
Thenus maculata	–0.356	0.156	0.351	–0.138	0.026	–0.017	0.066
Thenus orientalis	0.739	–0.186	–0.257	0.081	–0.121	–0.099	0.112
Trachypenaeus anchoralis	0.127	–0.420	0.067	–0.061	0.181	0.094	–0.051
Trachypenaeus granulosus	0.941	0.249	0.269	–0.039	–0.193	0.085	–0.031
Trachypenaeus sp.	0.048	–0.065	0.217	0.064	–0.200	0.001	–0.047
Molluscs							
Amusiidae	2.697	–1.045	–0.056	0.259	0.494	–0.146	–0.198
Annachlamys flabellata	0.706	–0.590	0.633	0.195	0.138	–0.016	0.040
Bivalvia	0.145	0.231	–0.270	–0.011	0.070	0.044	0.051
Octopoda	–0.271	0.132	0.216	0.000	0.001	0.019	0.063
Sepioidae	0.420	–0.127	–0.616	–0.126	0.042	0.064	–0.065
Teuthoidea	–0.223	0.159	–0.421	–0.013	0.164	–0.029	0.046
Echinoderms							
Asteroid (mixed spp.)	–0.421	0.089	–0.285	–0.108	–0.009	–0.079	0.078
Crinoidea	–1.008	0.367	0.052	–0.104	–0.003	–0.074	0.082
Gorgonocephalidae	–0.122	0.185	–0.018	–0.025	0.081	0.021	–0.018
Holothurioidea	–0.105	0.021	–0.017	–0.011	–0.032	0.025	0.068
Laganidae	0.142	0.073	–0.258	0.073	–0.013	–0.034	0.012
Spatangoida	0.285	–0.010	–0.001	0.051	–0.045	–0.045	–0.003
Ascidians							
Ascidiacea (mixed spp.)	–0.142	0.251	–0.135	–0.070	–0.018	0.042	–0.094

APPENDIX.3.C FULL SET OF SINGLE-SPECIES RESULTS FROM ANALYSIS OF COVARIANCE OF FISH SPECIES

Table App.3.C.1 Significance level for log-transformed weight for fish species present in at least 11 tows.

Species	*f*	mud	carbonate	depth	habitat	year	north vs south	closed vs open
Elasmobranchs								
Gymnura australis	11	< .001	.059	.602	.032	.342	.756	.372
Rhizoprionodon acutus	18	.006	.184	.261	.882	.465	.175	.145
Teleosts								
Abalistes stellaris	18	< .001	.243	.141	.775	.081	.657	.001
Alepes sp.	40	< .001	.536	.784	.665	.711	.583	.960
Atule mate	13	.628	.277	.084	.758	.799	.371	.161
Canthigaster compressa	25	< .001	.006	.010	.097	.009	< .001	.019
Carangoides caeruleopinnatus	35	< .001	.350	.539	.711	< .001	.480	.376
Carangoides chrysophrys	16	.029	.851	.008	.078	.391	.022	.951
Carangoides fulvoguttatus	25	.047	.003	.625	.132	.011	.411	.843
Carangoides gymnostethus	41	.680	.888	.357	.738	.422	.117	.893
Carangoides hedlandensis	46	< .001	.109	.992	.491	.017	.130	.057
Carangoides humerosus	41	< .001	.578	.512	.087	.688	.116	.193
Carangoides talamparoides	18	< .001	.792	.557	.427	.729	.047	.787
Caranx bucculentus	29	< .001	.186	.860	.560	.310	.002	.596
Centriscus scutatus	20	.120	.223	.067	.487	.526	.009	.753
Chaetodontoplus duboulayi	13	.004	.548	.202	.053	.811	.429	.118
Choerodon cephalotes	69	.038	.701	.187	.762	.078	.336	.525
Choerodon monostigma	18	.118	.001	.035	.918	.383	.523	.556
Choerodon sp.2	83	.087	.630	.053	.855	.055	.051	.386
Coradion chrysozonus	13	.038	.859	.038	.178	.885	.303	.375
Decapterus russellii	30	.392	.382	.341	.592	.768	.741	.571
Diagramma pictum	48	.001	.208	.563	.196	.848	.002	.652
Dussumieria elopsoides	27	< .001	.762	.481	.053	< .001	.058	.626
Echeneis naucrates	33	.998	.983	.304	.603	.346	.904	.120
Fistularia petimba	76	< .001	.136	.418	.939	.240	.011	.274
Gazza minuta	24	< .001	.860	.516	.582	.132	.135	.230
Gerres oyena	52	< .001	.147	.019	.858	.847	.240	.307
Glaucosoma magnificum	21	.052	.116	.728	.852	.803	.091	.791
Gnathanodon speciosus	26	.610	.917	.780	.408	.685	.028	.769
Herklotsichthys lippa	33	.005	.606	.790	.956	.011	.568	.138
Lactoria cornuta	11	.002	.186	.425	.541	.069	.201	.547
Lagocephalus sceleratus	58	.001	.924	.115	.027	.019	.091	.926
Leiognathus bindus	73	< .001	.149	.096	.547	.425	.321	.143
Leiognathus leuciscus	31	.001	.074	.001	.546	.410	.080	.562
Leiognathus sp.	93	< .001	.001	.014	.706	.814	.006	.292
Lethrinus genivittatus	139	.272	.187	.012	.123	.022	.047	.006
Lethrinus laticaudis	21	.391	.438	.305	.946	.235	.219	.835
Lutjanus malabaricus	11	.718	.550	.048	.341	.438	.319	.668
Lutjanus sebae	20	.001	.338	.646	.879	.097	.751	.184
Lutjanus vittus	29	.858	.081	.038	.186	.451	.185	.852
Mene maculata	19	.017	.956	.603	.388	.025	.003	.208
Nemipterus furcosus	127	< .001	.762	.316	.509	.590	.704	.463
Nemipterus hexodon	34	< .001	.068	.200	.197	.599	.024	.400
Nemipterus peronii	35	< .001	.886	.282	.925	.881	.120	.641

Species	***f***	**mud**	**carbonate**	**depth**	**habitat**	**year**	**north vs south**	**closed vs open**
Parachaetodon ocellatus	15	.935	.293	.199	.498	.090	.820	.468
Paramonacanthus choirocephalus	18	< .001	.960	.222	.121	< .001	.117	.966
Paramonacanthus japonicus	50	.008	.321	.405	.233	.554	.434	.763
Parupeneus heptacanthus	17	< .001	.180	.807	.443	.212	.211	.224
Pelates quadrilineatus	11	< .001	.243	.973	.334	.737	.533	.366
Pentapodus paradiseus	97	.004	.556	.951	.187	.527	.319	.572
Pentaprion longimanus	39	< .001	.249	.085	.191	.322	.104	.003
Platax batavianus	19	.001	.674	.906	.673	.746	.179	.461
Platax teira	15	.692	.621	.879	.715	.464	.645	.815
Plotosus lineatus	11	.682	.298	.947	.950	.981	.504	.887
Priacanthus tayenus	59	< .001	.554	.191	.823	.033	.860	.212
Pristotis jerdoni	44	< .001	.143	.578	.407	.548	.569	.071
Pseudomonacanthus peroni	11	.622	.259	.483	.246	.212	.146	.938
Rastrelliger kanagurta	40	< .001	.768	.076	.640	.032	.056	.551
Rhynchostracion nasus	17	.620	.719	.424	.180	.259	.167	.460
Saurida micropectoralis	19	.025	.120	.487	.341	.263	< .001	.008
Saurida undosquamis	113	< .001	.595	.280	.358	.026	.048	.403
Scolopsis affinis	17	< .001	.139	.547	.111	.851	.089	.120
Scolopsis taeniopterus	55	< .001	.682	.521	.152	.980	.051	.608
Scomberomorus munroi	12	.260	.543	.532	.155	.373	.718	.420
Scomberomorus queenslandicus	68	< .001	.051	.013	.668	.884	.815	.536
Selar boops	56	< .001	.809	.705	.369	.020	.308	.430
Selaroides leptolepis	113	< .001	.064	.019	.252	.785	.178	.695
Seriolina nigrofasciata	22	< .001	.646	.275	.112	.002	.292	.459
Siganus canaliculatus	107	< .001	.138	.188	.302	.150	.479	.746
Sphyraena flavicauda	15	.485	.001	.087	.127	.402	.376	.277
Sillago maculata	24	.851	.086	.629	.433	.126	.422	.277
Sphyraena forsteri	35	< .001	.680	.287	.776	.702	.502	.278
Synodus sageneus	16	.259	.911	.769	.799	.125	.410	.023
Tetrosomus gibbosus	15	< .001	.030	.135	.143	.498	.008	.538
Torquigener pallimaculatus	76	< .001	.250	.707	.574	.003	.221	.294
Trachinocephalus myops	13	.001	.226	.314	.171	.044	.752	.879
Upeneus asymmetricus	30	.902	.333	.869	.496	.692	.947	.007
Upeneus luzonius	44	< .001	.347	.522	.765	.016	.034	.022
Upeneus sulphureus	12	.001	.027	.630	.270	.498	.115	.042
Upeneus sundaicus	24	.006	.082	< .001	.011	.197	.021	.268
Upeneus tragula	34	.033	.430	.859	.979	.022	.828	.400
Uraspis uraspis	12	.003	.604	.033	.646	.057	.220	.786

Table App.3.C.2 Estimated coefficient for log-transformed weight for fish species present in at least 11 tows.

Species	mud	carbonate	depth	habitat	year	north vs south	closed vs open
Elasmobranchs							
Gymnura australis	0.332	0.158	0.055	–0.115	–0.030	–0.007	0.028
Rhizoprionodon acutus	0.449	–0.270	–0.292	0.019	–0.057	–0.080	0.113
Teleosts							
Abalistes stellaris	–0.984	0.266	0.429	0.042	–0.152	–0.029	0.296
Alepes sp.	0.875	0.155	0.088	0.069	–0.035	0.040	0.005
Atule mate	–0.113	–0.319	–0.650	0.058	–0.028	–0.076	0.157
Canthigaster compressa	–1.071	0.719	–0.856	0.274	–0.258	–0.313	–0.232
Carangoides caeruleopinnatus	0.913	0.262	0.220	0.066	–0.387	–0.057	0.095
Carangoides chrysophrys	0.238	0.026	0.463	0.154	0.044	–0.091	–0.003
Carangoides fulvoguttatus	–0.294	–0.564	–0.115	0.178	–0.182	–0.044	–0.014
Carangoides gymnostethus	0.083	0.035	0.296	–0.054	0.077	0.114	–0.013
Carangoides hedlandensis	1.065	–0.421	–0.003	–0.115	–0.239	–0.115	0.191
Carangoides humerosus	0.835	–0.110	0.165	–0.217	–0.030	–0.090	–0.098
Carangoides talamparoides	0.590	0.054	0.154	–0.105	0.027	–0.119	0.021
Caranx bucculentus	1.372	0.397	0.067	–0.112	–0.116	–0.276	–0.060
Centriscus scutatus	–0.285	0.279	0.538	–0.102	–0.055	0.175	–0.027
Chaetodontoplus duboulayi	–0.363	0.092	–0.251	0.191	–0.014	–0.035	0.092
Choerodon cephalotes	0.531	–0.122	–0.537	–0.061	–0.214	0.088	–0.077
Choerodon monostigma	0.222	–0.618	0.478	0.012	0.059	–0.033	–0.040
Choerodon sp.2	0.478	0.168	0.867	0.041	–0.256	0.197	–0.115
Coradion chrysozonus	–0.284	0.030	–0.454	0.147	0.009	–0.051	–0.057
Decapterus russellii	0.210	0.269	0.373	–0.105	0.034	0.029	0.066
Diagramma pictum	–1.363	0.622	0.364	0.408	0.036	–0.442	–0.084
Dussumieria elopsoides	0.758	–0.057	–0.171	0.237	–0.288	0.105	0.035
Echeneis naucrates	–0.001	0.007	0.422	–0.107	–0.115	–0.011	–0.191
Fistularia petimba	2.074	0.409	0.283	–0.013	0.123	0.202	0.114
Gazza minuta	0.715	0.036	–0.169	–0.072	–0.117	–0.088	–0.094
Gerres oyena	1.177	–0.431	–0.897	–0.034	–0.022	–0.101	0.115
Glaucosoma magnificum	0.326	–0.330	–0.093	–0.025	–0.020	0.102	–0.021
Gnathanodon speciosus	0.161	0.041	–0.141	0.209	–0.061	–0.252	0.044
Herklotsichthys lippa	0.641	–0.144	–0.095	0.010	0.274	0.046	0.159
Lactoria cornuta	–0.306	0.158	–0.121	–0.047	–0.083	–0.044	–0.027
Lagocephalus sceleratus	0.685	–0.023	–0.487	–0.344	–0.218	–0.118	0.009
Leiognathus bindus	3.310	–0.704	–1.038	–0.187	–0.148	–0.139	0.272
Leiognathus leuciscus	1.054	–0.692	–1.638	–0.149	–0.121	–0.196	0.085
Leiognathus sp.	5.371	–1.594	–1.485	0.113	–0.042	0.375	0.189
Lethrinus genivittatus	0.367	0.552	–1.346	0.413	–0.366	0.242	0.443
Lethrinus laticaudis	–0.148	–0.168	0.283	–0.009	–0.098	–0.077	–0.017
Lutjanus malabaricus	–0.062	–0.128	0.544	–0.131	–0.063	–0.062	–0.035
Lutjanus sebae	–0.893	0.309	0.189	–0.031	–0.204	–0.029	0.163
Lutjanus vittus	0.053	–0.652	0.995	–0.316	–0.107	–0.143	–0.026
Mene maculata	0.581	–0.017	0.200	–0.166	0.259	–0.262	–0.145
Nemipterus furcosus	1.287	0.130	0.550	–0.181	–0.088	–0.047	–0.120
Nemipterus hexodon	1.319	0.420	–0.375	–0.190	0.046	–0.151	0.073
Nemipterus peronii	0.741	–0.029	0.282	–0.012	0.012	–0.092	–0.036
Parachaetodon ocellatus	–0.010	–0.160	0.250	0.066	–0.099	–0.010	0.042
Paramonacanthus choirocephalus	0.406	0.006	–0.198	0.126	0.214	–0.057	0.002
Paramonacanthus japonicus	0.512	–0.237	–0.253	0.182	–0.054	0.054	0.027
Parupeneus heptacanthus	–0.672	0.253	0.059	0.092	–0.089	–0.068	0.087
Pelates quadrilineatus	0.943	0.302	–0.011	–0.160	–0.033	–0.046	0.089

Species	**mud**	**carbonate**	**depth**	**habitat**	**year**	**north vs south**	**closed vs open**
Pentapodus paradiseus	–0.986	0.249	0.033	0.356	–0.102	0.121	–0.091
Pentaprion longimanus	1.482	–0.328	0.627	–0.238	–0.107	–0.134	0.324
Platax batavianus	–0.658	0.103	0.037	0.066	–0.030	–0.095	–0.069
Platax teira	–0.050	0.078	–0.031	–0.037	0.044	–0.021	0.014
Plotosus lineatus	0.080	–0.255	0.021	0.010	0.002	0.047	0.013
Priacanthus tayenus	1.666	–0.162	0.457	–0.039	–0.224	–0.014	–0.130
Pristotis jerdoni	–1.227	0.509	–0.246	0.184	0.079	–0.057	0.239
Pseudomonacanthus peroni	0.040	0.116	0.092	–0.076	–0.049	0.043	0.003
Rastrelliger kanagurta	0.618	–0.064	–0.492	–0.065	0.177	–0.120	–0.049
Rhynchostracion nasus	0.120	–0.109	–0.309	0.260	–0.130	–0.121	–0.085
Saurida micropectoralis	0.267	–0.231	–0.131	–0.090	–0.063	–0.193	–0.152
Saurida undosquamis	1.340	0.136	–0.352	–0.150	–0.218	–0.147	–0.081
Scolopsis affinis	–0.633	0.263	–0.136	0.181	–0.013	–0.087	0.105
Scolopsis taeniopterus	1.367	0.116	0.232	–0.259	–0.003	–0.161	–0.055
Scomberomorus munroi	0.112	–0.076	–0.099	–0.113	–0.042	–0.013	–0.038
Scomberomorus queenslandicus	0.864	–0.461	–0.748	–0.064	0.013	0.016	0.055
Selar boops	2.271	–0.101	–0.201	–0.239	–0.372	–0.123	–0.125
Selaroides leptolepis	3.238	–0.857	–1.391	–0.338	0.048	0.180	0.069
Seriolina nigrofasciata	0.514	–0.070	0.213	0.156	–0.186	0.046	0.043
Siganus canaliculatus	2.133	–0.567	–0.642	0.252	–0.210	0.078	–0.047
Sillago maculata	–0.075	–0.438	–0.294	–0.132	0.043	–0.034	0.056
Sphyraena flavicauda	–0.047	–0.539	–0.193	–0.157	–0.183	0.073	0.129
Sphyraena forsteri	1.309	0.131	–0.430	0.057	–0.046	0.061	0.131
Synodus sageneus	0.146	–0.018	–0.061	0.026	–0.095	–0.039	–0.141
Tetrosomus gibbosus	–0.383	0.255	–0.223	0.109	–0.030	–0.091	–0.027
Torquigener pallimaculatus	2.141	0.376	0.157	–0.117	–0.369	–0.116	–0.131
Trachinocephalus myops	–0.274	–0.123	0.130	–0.089	0.078	0.009	0.006
Upeneus asymmetricus	–0.029	–0.290	–0.063	–0.130	–0.045	0.006	0.312
Upeneus luzonius	–1.072	–0.281	0.244	0.057	–0.276	–0.184	0.263
Upeneus sulphureus	0.333	–0.267	0.074	0.085	0.031	0.055	0.094
Upeneus sundaicus	0.395	–0.312	–0.860	–0.294	–0.088	–0.120	0.075
Upeneus tragula	0.484	–0.223	0.064	0.005	–0.247	0.018	0.090
Uraspis uraspis	0.381	0.083	0.437	–0.047	0.117	–0.057	0.016

Table App.3.C.3 Significance level for log-transformed number for fish species present in at least 11 tows.

Species	*f*	mud	carbonate	depth	habitat	year	north vs south	closed vs open
Elasmobranchs								
Gymnura australis	11	< .001	.093	.515	.055	.521	.934	.364
Rhizoprionodon acutus	18	.019	.154	.184	.945	.558	.276	.085
Teleosts								
Abalistes stellaris	18	< .001	.242	.195	.834	.079	.598	.003
Alepes sp.	40	< .001	.513	.859	.648	.691	.578	.863
Atule mate	13	.668	.149	.079	.892	.899	.511	.121
Canthigaster compressa	25	< .001	.003	.002	.088	.041	< .001	.005
Carangoides caeruleopinnatus	35	< .001	.415	.773	.739	< .001	.463	.370
Carangoides chrysophrys	16	.020	.825	.125	.123	.472	.038	.831
Carangoides fulvoguttatus	25	.111	.002	.267	.111	.015	.649	.939
Carangoides gymnostethus	41	.661	.930	.534	.630	.330	.066	.906
Carangoides hedlandensis	46	< .001	.173	.578	.337	.023	.166	.048
Carangoides humerosus	41	< .001	.766	.762	.090	.383	.075	.125
Carangoides talamparoides	18	< .001	.581	.940	.485	.851	.031	.917
Caranx bucculentus	29	< .001	.240	.885	.400	.229	.001	.475
Centriscus scutatus	20	.153	.235	.097	.402	.526	.013	.761
Chaetodontoplus duboulayi	13	.009	.742	.238	.073	.804	.696	.113
Choerodon cephalotes	69	.011	.414	.187	.637	.024	.220	.317
Choerodon monostigma	18	.205	< .001	.049	.935	.542	.669	.811
Choerodon sp.2	83	.095	.830	.055	.980	.029	.056	.327
Coradion chrysozonus	13	.045	.991	.028	.283	.725	.407	.537
Decapterus russellii	30	.561	.427	.242	.661	.904	.535	.387
Diagramma pictum	48	.155	.575	.354	.167	.024	.016	.736
Dussumieria elopsoides	27	< .001	.763	.483	.047	< .001	.056	.529
Echeneis naucrates	33	.986	.512	.313	.887	.471	.530	.091
Fistularia petimba	76	< .001	.145	.592	.994	.177	.015	.166
Gazza minuta	24	< .001	.905	.387	.664	.160	.116	.243
Gerres oyena	52	< .001	.114	.006	.705	.642	.264	.206
Glaucosoma magnificum	21	.036	.215	.402	.906	.866	.058	.676
Gnathanodon speciosus	26	.999	.785	.262	.730	.153	.022	.526
Herklotsichthys lippa	33	.013	.440	.601	.865	.011	.736	.143
Lactoria cornuta	11	.002	.210	.260	.538	.046	.179	.570
Lagocephalus sceleratus	58	.001	.820	.119	.014	.016	.181	.656
Leiognathus bindus	73	< .001	.183	.037	.398	.252	.301	.161
Leiognathus leuciscus	31	.004	.041	< .001	.420	.430	.064	.465
Leiognathus sp.	93	< .001	< .001	.005	.691	.429	.007	.219
Lethrinus genivittatus	139	.436	.370	.010	.135	.020	.038	.004
Lethrinus laticaudis	21	.671	.252	.352	.792	.227	.284	.819
Lutjanus malabaricus	11	.990	.533	.138	.995	.151	.461	.823
Lutjanus sebae	20	.037	.735	.428	.576	.101	.975	.343
Lutjanus vittus	29	.565	.056	.064	.128	.544	.245	.846
Mene maculata	19	.021	.961	.550	.423	.029	.004	.243
Nemipterus furcosus	127	.001	.946	.164	.486	.392	.818	.747
Nemipterus hexodon	34	< .001	.294	.096	.131	.473	.042	.500
Nemipterus peronii	35	< .001	.530	.499	.689	.715	.073	.652
Parachaetodon ocellatus	15	.950	.126	.477	.514	.221	.851	.493
Paramonacanthus choirocephalus	18	< .001	.963	.186	.162	< .001	.141	.874
Paramonacanthus japonicus	50	.006	.207	.374	.270	.468	.452	.583
Parupeneus heptacanthus	17	< .001	.171	.663	.513	.097	.168	.160
Pelates quadrilineatus	11	< .001	.228	.956	.347	.747	.551	.364

Species	***f***	**mud**	**carbonate**	**depth**	**habitat**	**year**	**north vs south**	**closed vs open**
Pentapodus paradiseus	97	.003	.872	.937	.147	.453	.268	.607
Pentaprion longimanus	39	< .001	.213	.139	.217	.362	.120	.003
Platax batavianus	19	.001	.422	.740	.817	.489	.160	.352
Platax teira	15	.781	.636	.478	.709	.408	.696	.665
Plotosus lineatus	11	.636	.351	.952	.897	.902	.352	.728
Priacanthus tayenus	59	< .001	.970	.275	.771	.053	.569	.227
Pristotis jerdoni	44	< .001	.155	.629	.441	.523	.590	.061
Pseudomonacanthus peroni	11	.205	.191	.528	.298	.213	.168	.836
Rastrelliger kanagurta	40	< .001	.864	.051	.614	.023	.050	.528
Rhynchostracion nasus	17	.411	.539	.449	.243	.096	.177	.837
Saurida micropectoralis	19	.031	.136	.299	.259	.288	< .001	.008
Saurida undosquamis	113	< .001	.869	.609	.347	.046	.104	.558
Scolopsis affinis	17	< .001	.117	.512	.101	.897	.074	.132
Scolopsis taeniopterus	55	< .001	.954	.901	.095	.999	.072	.812
Scomberomorus munroi	12	.317	.430	.555	.071	.597	.639	.541
Scomberomorus queenslandicus	68	< .001	.118	.036	.945	.645	.596	.186
Selar boops	56	< .001	.799	.708	.379	.002	.303	.564
Selaroides leptolepis	113	< .001	.039	.008	.249	.874	.144	.549
Seriolina nigrofasciata	22	< .001	.821	.294	.227	.001	.367	.391
Siganus canaliculatus	107	< .001	.092	.110	.317	.292	.363	.809
Sillago maculata	15	.355	.001	.047	.081	.648	.281	.300
Sphyraena flavicauda	24	.651	.050	.631	.445	.162	.412	.201
Sphyraena forsteri	35	< .001	.715	.425	.864	.738	.508	.214
Synodus sageneus	16	.233	.967	.591	.644	.110	.362	.020
Tetrosomus gibbosus	15	< .001	.024	.121	.155	.371	.004	.500
Torquigener pallimaculatus	76	< .001	.311	.902	.552	.001	.272	.633
Trachinocephalus myops	13	.002	.113	.353	.161	.030	.527	.978
Upeneus asymmetricus	30	.826	.323	.812	.429	.704	.966	.007
Upeneus luzonius	44	< .001	.310	.594	.829	.017	.042	.013
Upeneus sulphureus	12	.001	.019	.673	.257	.521	.122	.040
Upeneus sundaicus	24	.024	.051	< .001	.007	.181	.027	.239
Upeneus tragula	34	.062	.286	.985	.942	.014	.826	.355
Uraspis uraspis	12	.002	.771	.061	.464	.052	.269	.590

Table App.3.C.4 Estimated coefficient for log-transformed number for fish species present in at least 11 tows.

Species	mud	carbonate	depth	habitat	year	north vs south	closed vs open
Elasmobranchs							
Gymnura australis	0.277	0.126	0.062	–0.092	–0.018	0.002	0.026
Rhizoprionodon acutus	0.155	–0.118	–0.140	–0.004	–0.018	–0.026	0.054
Teleosts							
Abalistes stellaris	–0.505	0.144	0.203	0.016	–0.082	–0.019	0.140
Alepes sp.	0.976	0.177	0.061	0.079	–0.041	0.043	0.018
Atule mate	–0.047	–0.200	–0.311	0.012	–0.007	–0.026	0.082
Canthigaster compressa	–0.795	0.605	–0.802	0.223	–0.159	–0.286	–0.220
Carangoides caeruleopinnatus	0.807	0.198	0.090	0.052	–0.366	–0.052	0.083
Carangoides chrysophrys	0.289	0.034	0.304	0.153	0.042	–0.093	–0.013
Carangoides fulvoguttatus	–0.189	–0.467	–0.210	0.151	–0.138	–0.019	–0.004
Carangoides gymnostethus	0.068	0.017	0.153	–0.059	0.072	0.103	–0.009
Carangoides hedlandensis	0.835	–0.284	–0.147	–0.128	–0.182	–0.083	0.157
Carangoides humerosus	0.870	–0.055	0.071	–0.200	–0.061	–0.095	–0.107
Carangoides talamparoides	0.541	0.105	–0.018	–0.085	0.014	–0.119	–0.008
Caranx bucculentus	1.162	0.311	0.049	–0.142	–0.121	–0.248	–0.072
Centriscus scutatus	–0.196	0.204	0.365	–0.092	–0.041	0.124	–0.020
Chaetodontoplus duboulayi	–0.264	0.041	–0.188	0.144	–0.012	–0.014	0.076
Choerodon cephalotes	0.513	–0.204	–0.422	–0.075	–0.217	0.089	–0.095
Choerodon monostigma	0.135	–0.501	0.336	0.007	0.031	–0.016	–0.012
Choerodon sp.2	0.365	0.059	0.671	–0.004	–0.228	0.152	–0.102
Coradion chrysozonus	–0.177	0.001	–0.310	0.075	0.015	–0.026	–0.026
Decapterus russellii	0.121	0.208	0.390	–0.073	0.012	0.047	0.086
Diagramma pictum	–0.242	0.119	0.252	0.189	0.184	–0.150	–0.027
Dussumieria elopsoides	0.853	–0.062	–0.184	0.263	–0.311	0.114	0.049
Echeneis naucrates	–0.002	–0.096	0.188	–0.013	–0.040	0.026	–0.094
Fistularia petimba	1.983	0.371	0.174	–0.001	0.131	0.181	0.134
Gazza minuta	0.600	0.022	–0.204	–0.051	–0.099	–0.084	–0.082
Gerres oyena	1.040	–0.450	–1.011	–0.069	–0.050	–0.092	0.137
Glaucosoma magnificum	0.345	–0.254	–0.219	–0.015	0.013	0.113	–0.033
Gnathanodon speciosus	0.000	0.061	–0.322	0.050	–0.122	–0.149	0.054
Herklotsichthys lippa	0.537	–0.208	–0.180	–0.029	0.264	0.026	0.151
Lactoria cornuta	–0.184	0.092	–0.106	–0.029	–0.056	–0.029	–0.016
Lagocephalus sceleratus	0.700	–0.057	–0.497	–0.396	–0.230	–0.096	0.042
Leiognathus bindus	2.864	–0.587	–1.179	–0.237	–0.192	–0.131	0.235
Leiognathus leuciscus	0.700	–0.611	–1.415	–0.154	–0.089	–0.160	0.083
Leiognathus sp.	4.500	–1.457	–1.478	0.104	–0.123	0.320	0.191
Lethrinus genivittatus	0.247	0.357	–1.322	0.382	–0.354	0.240	0.442
Lethrinus laticaudis	–0.071	–0.242	0.250	–0.035	–0.097	–0.065	–0.018
Lutjanus malabaricus	0.001	–0.062	0.189	0.000	–0.055	–0.021	–0.008
Lutjanus sebae	–0.231	0.047	0.139	–0.049	–0.086	0.001	0.050
Lutjanus vittus	0.115	–0.480	0.593	–0.243	–0.058	–0.084	–0.018
Mene maculata	0.505	–0.013	0.207	–0.139	0.227	–0.228	–0.121
Nemipterus furcosus	0.936	0.024	0.616	–0.154	–0.113	–0.023	–0.042
Nemipterus hexodon	0.850	0.173	–0.352	–0.160	0.045	–0.098	0.042
Nemipterus peronii	0.697	–0.122	0.167	–0.050	–0.027	–0.101	–0.033
Parachaetodon ocellatus	–0.007	–0.206	0.122	0.056	–0.063	0.007	0.035
Paramonacanthus choirocephalus	0.381	–0.006	–0.206	0.109	0.206	–0.052	0.007
Paramonacanthus japonicus	0.510	–0.292	–0.262	0.163	–0.064	0.050	0.048
Parupeneus heptacanthus	–0.584	0.212	0.086	0.065	–0.098	–0.062	0.083

Species	**mud**	**carbonate**	**depth**	**habitat**	**year**	**north vs south**	**closed vs open**
Pelates quadrilineatus	0.928	0.298	–0.017	–0.148	–0.030	–0.042	0.085
Pentapodus paradiseus	–0.986	0.066	0.041	0.378	–0.116	0.130	–0.079
Pentaprion longimanus	1.473	–0.363	0.551	–0.230	–0.101	–0.131	0.330
Platax batavianus	–0.283	0.087	–0.046	0.016	–0.028	–0.044	–0.038
Platax teira	–0.025	0.053	–0.101	–0.027	0.035	–0.013	0.018
Plotosus lineatus	0.073	–0.179	–0.015	–0.016	0.009	0.052	–0.025
Priacanthus tayenus	1.466	–0.009	0.327	–0.044	–0.174	–0.039	–0.108
Pristotis jerdoni	–1.197	0.486	–0.210	0.168	0.083	–0.053	0.244
Pseudomonacanthus peroni	0.105	0.135	0.083	–0.069	–0.049	0.041	0.008
Rastrelliger kanagurta	0.605	–0.035	–0.513	–0.066	0.178	–0.116	–0.049
Rhynchostracion nasus	0.086	–0.080	–0.126	0.097	–0.083	–0.051	0.010
Saurida micropectoralis	0.280	–0.242	–0.214	–0.117	–0.065	–0.204	–0.164
Saurida undosquamis	1.684	0.040	–0.160	–0.147	–0.187	–0.115	–0.055
Scolopsis affinis	–0.628	0.269	–0.143	0.180	–0.008	–0.089	0.098
Scolopsis taeniopterus	1.121	0.014	–0.040	–0.268	0.000	–0.131	–0.023
Scomberomorus munroi	0.068	–0.067	–0.064	–0.098	–0.017	–0.011	–0.020
Scomberomorus queenslandicus	1.150	–0.432	–0.742	0.012	0.048	0.042	0.139
Selar boops	2.028	–0.096	–0.181	–0.213	–0.449	–0.113	–0.083
Selaroides leptolepis	3.066	–0.923	–1.527	–0.329	0.027	0.188	0.101
Seriolina nigrofasciata	0.518	–0.034	0.203	0.117	–0.195	0.039	0.049
Siganus canaliculatus	2.056	–0.576	–0.697	0.218	–0.137	0.090	–0.031
Sillago maculata	–0.100	–0.458	–0.343	–0.151	0.023	–0.042	0.053
Sphyraena flavicauda	–0.100	–0.544	–0.169	–0.135	–0.147	0.065	0.135
Sphyraena forsteri	1.002	0.086	–0.240	0.026	–0.030	0.045	0.112
Synodus sageneus	0.122	–0.005	–0.087	0.038	–0.078	–0.034	–0.113
Tetrosomus gibbosus	–0.380	0.259	–0.226	0.104	–0.039	–0.095	–0.029
Torquigener pallimaculatus	1.743	0.265	0.041	–0.099	–0.323	–0.083	–0.047
Trachinocephalus myops	–0.209	–0.132	0.098	–0.075	0.069	0.015	–0.001
Upeneus asymmetricus	–0.050	–0.280	–0.086	–0.143	–0.041	0.003	0.295
Upeneus luzonius	–1.037	–0.290	0.194	0.039	–0.262	–0.169	0.272
Upeneus sulphureus	0.310	–0.274	0.062	0.084	0.028	0.052	0.092
Upeneus sundaicus	0.314	–0.340	–0.906	–0.305	–0.088	–0.112	0.078
Upeneus tragula	0.369	–0.264	0.006	0.011	–0.232	0.016	0.087
Uraspis uraspis	0.302	0.036	0.293	–0.057	0.091	–0.039	0.025

APPENDIX.3.D FULL SET OF SINGLE-SPECIES RESULTS FROM ANALYSIS OF COVARIANCE OF BENTHIC INVERTEBRATES FROM DREDGE

Table App.3.D.1 Significance level for log-transformed weight for benthic invertebrate species present in at least 11 hauls.

Species	*f*	mud	carbonate	depth	habitat	year	north vs south	closed vs open
Algae								
Halimeda discoidea	14	.052	.034	.002	.342	.026	.001	.190
Sponges								
Club sponge sp.1	20	.118	.309	.488	.246	.140	.287	.399
Ianthella sp.	13	.373	.668	.148	.003	.593	.246	.599
Porifera	24	.088	.730	.766	.032	.938	.565	.589
Porifera sp.8	11	.895	.341	.026	.004	.158	<.001	.014
Porifera sp.10	59	.837	.558	.451	.017	.008	.455	.433
Porifera sp.14	15	.129	.425	.819	.013	.386	.482	.863
Porifera sp.18	21	.005	.301	.834	.206	.030	.392	.171
Porifera sp.36	40	<.001	.410	.930	<.001	.802	.178	.772
Porifera sp.42	26	.105	.128	.309	.001	.758	.001	.742
Porifera sp.46	14	.348	.034	.571	.100	.421	.091	.584
Porifera sp.47	11	.576	.297	.268	.618	.201	.838	.105
Porifera sp.49	24	.831	.522	.105	.168	.129	.424	.771
Porifera sp.75/62	20	.173	.643	.067	<.001	.123	<.001	.075
Porifera sp.121	12	.020	.548	.728	.047	.081	.801	.092
Porifera sp.123	12	.066	.301	.526	.024	.657	.816	.744
Cnidarians								
Alcyonarian sp.1	63	.738	.749	.781	.033	.675	.525	.201
Alcyonarian sp.2	20	.009	.343	.443	.347	.656	.037	.940
Alcyonarian sp.3	43	.001	.710	.412	.208	.887	.166	.461
Alcyonarian sp.4	39	.044	.875	.463	.267	.021	.594	.810
Alcyonarian sp.8	35	.634	.302	.441	.133	<.001	.677	.334
Alcyonarian sp.10	41	.001	.608	.025	.149	.942	.009	.917
Alcyonarian sp.11	43	.614	.777	.209	.200	.203	.012	.084
Alcyonarian sp.15	33	.693	.088	<.001	.851	.235	.985	.354
Alcyonarian sp.18	12	.151	.568	.164	.095	.001	.072	.358
Alcyonarian sp.19	14	.693	.119	.090	.012	.075	.153	.551
Flabellum sp.	63	<.001	.539	<.001	.856	.491	<.001	.524
Fungia sp.1	64	<.001	<.001	<.001	.032	.040	.067	.283
Fungia sp.3	16	<.001	.136	.889	.277	.219	.049	.532
Fungia sp.4	18	.017	.256	<.001	.624	.083	.030	.756
Gorgonian sp.3	21	.062	.263	.075	.005	.992	.294	.894
Hydroid sp.5	22	.116	.105	.240	.070	.534	.940	.666
Hydroid sp.9	52	.004	.847	.180	.093	.158	.111	.295
Sphaenopus sp.1	123	.019	.027	.504	.555	.136	.001	.405
Crustaceans								
Calappa sp.2	11	.005	.459	.323	.878	.763	.424	.914
Calappa terraereginae	49	<.001	.524	.265	.247	.257	.605	.647
Charybdis jaubertensis	12	.261	.891	.329	.109	.334	.108	.516
Cryptopodia sp.3	30	.021	.003	.743	.675	.610	.854	.432
Dardanus imbricata	42	.001	.840	.145	.453	.370	.435	.144
Diogenes sp.3	20	.865	.437	.348	.163	<.001	.330	.336
Dorippe frascone	34	.104	.486	.031	.311	.218	.098	.420
Hyastenus sp.1	12	.001	.838	.680	.218	.245	.408	.185

Species	*f*	mud	carbonate	depth	habitat	year	north vs south	closed vs open
Hyastenus sp.4	23	.556	.048	.465	.517	.758	.055	.100
Ixa inermis	14	.451	.475	.163	.551	.115	.448	.908
Leucosia ocellata	35	.001	.400	.515	.881	.006	.983	.022
Metapenaeopsis palmensis	41	.048	.461	.827	.685	.332	.032	.275
Metapenaeus endeavouri	27	<.001	.284	.408	.925	.021	.832	.718
Pagurid	11	.066	.070	<.001	.056	.742	.002	.245
Parthenope harpax	25	.789	.652	.213	.456	.436	.572	.245
Parthenope hoplonotus	26	.012	.001	.198	.263	.138	.767	.134
Parthenope longimanus	39	<.001	.137	.377	.253	.029	.315	.844
Parthenope longispinus	14	.518	.153	.197	.973	.680	.838	.904
Penaeus esculentus	33	<.001	.279	.115	.139	.225	.220	.109
Penaeus latisulcatus	11	.346	.007	.529	.946	.576	.236	.084
Penaeus longistylus	17	.120	.317	.271	.927	.621	.229	.298
Phalangipes australiensis	25	.324	.421	.050	.818	.676	.058	.059
Phalangipes longipes	15	<.001	.322	.252	.366	.128	.652	.528
Pilumnus semilanatus	11	.706	.791	.847	.003	.472	.299	.963
Pilumnus sp.1	17	.413	.917	.466	.082	.776	.457	.211
Portunus gracilimanus	41	<.001	.412	.265	.009	.291	.021	.669
Portunus pelagicus	11	.625	.168	.652	.658	.269	.556	.463
Portunus rubromarginatus	81	.060	.473	.616	.358	.194	.077	.315
Portunus tenuipes	69	<.001	.219	.397	.491	.976	.004	.645
Scyllarus demani	21	.575	.524	.315	.036	.259	<.001	.036
Spiropagurus sp.3	15	.389	.957	.825	.402	.002	.023	.037
Thalamita sima	13	.047	.458	.374	.185	.480	.165	.801
Thenus orientalis	23	.188	.075	.520	.273	.770	.857	.964
Trachypenaeus granulosus	24	.001	.614	.188	.643	.529	.336	.951
Molluscs								
Amusium pleuronectes	70	<.001	.042	.813	.310	.403	.060	.734
Annachlamys flabellata	22	.040	.002	.658	.274	.336	.261	.547
Antigonia lamellaris	47	<.001	.155	.455	.067	.426	.022	.610
Arca navicularis	18	.910	.006	.057	.977	.175	.929	.172
Barbatia foliata	12	.311	.642	.909	.198	.065	.503	.244
Bassina calophylla	53	<.001	.012	.244	.022	.177	.693	.451
Bursa rana	23	.006	.815	.447	.030	.233	.112	.259
Chicoreus banksii	13	.002	.651	.213	.002	<.001	.015	.470
Chicoreus cervicornis	65	<.001	.794	.085	.191	.120	<.001	.904
Circe scripta	12	.413	.665	.397	.672	.983	.156	.436
Cronia contracta	12	.438	.240	.349	.115	.021	.904	.036
Ctenocardia virgo	13	.050	.298	.021	.325	.887	.005	.050
Cucullaea labiata	26	<.001	.038	.930	.771	.401	.742	.218
Cymbiola sophia	46	.045	.027	.062	.590	.819	<.001	.594
Dendostraea folium	11	.919	.530	.629	.669	.001	.880	.711
Distorsio reticularis	19	.243	.120	.392	.078	.987	.005	.414
Dosinia altenai	44	<.001	.071	.837	.105	.408	.805	.872
Dosinia juvinilis	14	.060	.210	.463	.154	.901	.092	.454
Echelus atratus	14	.042	.519	.020	.635	.428	.295	.312
Fragum retusum	20	.043	.007	<.001	.388	.089	.238	.515
Hyatina hyotis	26	.023	.053	.548	.102	.051	.138	.026
Lophiotoma indica	18	.118	.149	.202	.245	.701	.980	.144
Malleus albus	29	.016	.299	.316	.226	.396	.303	.812
Melaxinia vitrea	66	<.001	.206	.541	.496	.005	.019	.160
Modiolus ostentatus	18	<.001	.483	.508	.761	.007	.235	.043
Murex macgillivrayi	24	.006	.982	.144	.958	.325	.036	.553
Paphia semirugata	29	<.001	.489	.695	.692	.923	.039	.094
Pinctada fucata	11	.001	.193	.210	.284	.276	.801	.061
Placuna lincolni	16	.002	.576	.650	.163	.680	.528	.598
Plicatula essingtonensis	26	.010	.590	.924	<.001	.021	.026	.467
Pteria zebra	15	.520	.052	.370	.501	<.001	.011	.370

Species	***f***	**mud**	**carbonate**	**depth**	**habitat**	**year**	**north vs south**	**closed vs open**
Sepioidea sp.1	24	.001	.376	.491	.380	.296	.042	.349
Sepioidea sp.2	23	.098	.280	.569	.889	.250	.358	.334
Sepioidea sp.3	11	.886	.825	.242	.705	.013	.009	.008
Spondylus wrightianus	32	.010	.329	.021	.996	.931	.453	.706
Strombus diliatus	19	.175	.118	.138	.571	.791	.890	.159
Strombus vittatus	55	.316	.664	.143	.929	.016	.034	.076
Trisidos semitorta	22	<.001	.327	.544	.092	.876	.666	.130
Vepricardium multispinosum	31	<.001	.175	.413	.507	<.001	.890	.794
Volva volva	18	.107	.864	.293	.496	.054	.845	.381
Xenophora solarioides	35	.206	.118	.016	.402	.371	.654	.511
Bryozoans								
Amathia sp.	13	.290	.632	.761	.481	.018	.037	.995
Bryozoan sp.2	11	.041	.519	.340	.028	.069	.064	.310
Bryozoan sp.3	21	.353	.649	.779	.869	.007	.518	.995
Bryozoan sp.6	32	.663	.803	.245	.005	<.001	.047	.092
Bryozoan sp.8	17	.400	.062	.205	.402	.499	.442	.022
Bryozoan sp.9	34	<.001	.776	.665	.633	.391	.139	.569
Bryozoan sp.18	14	.283	.853	.280	.009	.005	.686	.029
Bryozoan sp.23	34	<.001	.121	.473	.061	<.001	.401	.172
Retiflustia cornea	27	.131	.437	.453	.519	.095	.211	.795
Scrupocellaria sp.	20	.003	.073	.609	.040	.010	.921	.003
Triphyllozoon sp.	32	.001	.121	.969	.579	.572	.805	.699
Echinoderms								
Asteroid (mixed spp.)	19	.929	.624	.428	.203	.308	.018	.040
Asteroid sp.11	11	.513	.860	.004	.929	.038	.439	.126
Astropecten granulatus	79	<.001	.435	.435	.882	.326	.969	.947
Astropecten sp.4	61	<.001	.282	.047	.069	.087	.024	.808
Brissopsis sp.2	57	<.001	.125	.214	.848	.764	.339	.665
Brissopsis sp.ss	18	.008	.453	.487	.625	.352	.482	.388
Crinoid sp.12	13	.011	.522	.447	.300	.019	.065	.428
Crinoid sp.15	63	<.001	.006	.907	.338	.600	.304	.428
Crinoid sp.16	14	.777	.187	.044	.858	.154	.482	.688
Crinoid sp.17	77	<.001	<.001	.661	.405	.168	.576	.187
Crinoid sp.19	45	<.001	.007	.734	.755	.191	.575	.048
Crinoid sp.21	21	<.001	.174	.019	.709	.121	.030	.193
Crinoid sp.22	28	.331	.316	.788	.480	.610	.492	.712
Crinoid sp.26	23	.045	.088	.632	.902	.996	.394	.309
Crinoid sp.27	39	<.001	.022	.155	.040	.089	.013	.887
Crinoid sp.5	62	<.001	.004	.230	.044	.005	.004	.021
Crinoidea	13	.080	.929	.451	.850	.599	.025	.761
Echinoid sp.3	13	.853	.845	.174	.849	.974	.523	.905
Echinoid sp.6	17	.527	.972	.693	.199	.713	.449	.167
Euretaster insignis	21	.754	.327	.218	.741	.012	.223	.673
Gorgonocephalid sp.1	28	<.001	.754	.001	.493	.711	.837	.072
Holothuria ocellata	47	<.001	.275	.110	.278	.472	.164	.691
Holothurian sp.3	11	.011	.112	.361	.755	.533	.542	.869
Holothurian sp.38	22	.047	.067	.045	.472	.014	.254	.312
Iconaster longimanus	34	.468	.519	.043	.250	.034	<.001	.554
Laganum sp.2	44	.508	.523	.080	.397	.063	.613	.155
Laganum sp.3	86	<.001	.795	.030	.331	.022	.161	.437
Laganum sp.8	55	<.001	.274	.145	.241	.163	.004	.497
Luidia maculata	12	.220	.622	.048	.323	.632	.966	.866
Maretia ovata	35	<.001	.293	.196	.663	.059	.196	.339
Metrodira subulata	66	.187	.909	.454	.173	.193	.001	.384
Ophiuroid sp.1	52	.008	.934	.300	.941	.344	.944	.795
Ophiuroid sp.34	30	<.001	.249	.393	.003	.694	.900	.020
Ophiuroid sp.5	15	.581	.753	.195	.154	.002	.111	.387
Pentaceraster sp.	13	.010	.825	.097	.107	.226	.291	.042

Species	***f***	**mud**	**carbonate**	**depth**	**habitat**	**year**	**north vs south**	**closed vs open**
Pentacta anceps	43	.001	.059	.181	.595	.991	.584	.101
Prionocidaris sp.2	29	.792	.366	.142	.610	.038	.064	.012
Stellaster equestris	94	.065	.427	.022	.398	.007	<.001	.603
Ascidians								
Ascidia scaevola	23	.348	.531	.852	.178	.160	.093	.764
Ascidia sydneiensis	37	<.001	.745	.037	.338	.920	.535	.088
Ascidian sp.1	38	<.001	.692	.647	.555	.045	.075	.288
Cemidocarpa stolonifera	14	.100	.690	.163	.795	.124	.593	.610
Herdmania momus	42	<.001	.153	.380	.005	.180	<.001	.276
Hypodistoma deerratum	32	.070	.168	.097	.139	.418	.982	.777
Microcosmus exasperatus	19	.955	.110	.001	.389	.983	.209	.254
Microcosmus helleri	19	.198	.091	.151	.775	<.001	.269	.142
Phallusia millari	60	<.001	.442	.946	.586	.407	.002	.466
Polycarpa chinensis	32	.018	.680	.460	.939	.039	.676	.276
Polycarpa papillata	38	.976	.255	.243	.707	.534	.036	.974
Pseudodistoma sp.	28	.002	.952	.187	.189	.375	.566	.789
Pyura sacciformis	19	.002	.667	.087	.733	.516	.851	.019
Rhopalaea tenuis	18	.882	.017	.067	.918	.007	.612	.204

Table App.3.D.2 Estimated coefficient for log-transformed weight for benthic invertebrate species present in at least 11 hauls.

Species	mud	carbonate	depth	habitat	year	north vs south	closed vs open
Algae							
Halimeda discoidea	–0.335	0.447	–0.861	0.128	0.181	–0.207	–0.106
Sponges							
Club sponge 1	0.209	0.165	–0.149	0.122	0.093	0.051	0.053
Ianthella sp.	–0.096	–0.056	0.252	0.253	–0.027	–0.045	–0.027
Porifera	0.478	0.117	0.133	0.473	0.010	–0.057	–0.071
Porifera sp.8	–0.022	0.190	–0.590	0.377	0.110	–0.221	–0.192
Porifera sp.10	–0.050	0.173	0.294	0.462	–0.309	–0.065	0.089
Porifera sp.14	–0.294	–0.187	0.071	0.381	–0.079	–0.048	–0.016
Porifera sp.18	0.368	–0.162	–0.043	–0.128	–0.132	0.039	0.083
Porifera sp.36	0.903	–0.207	–0.029	1.551	0.024	0.100	0.028
Porifera sp.42	–0.315	0.359	–0.316	0.509	–0.028	–0.230	–0.030
Porifera sp.46	0.079	–0.218	–0.076	0.109	–0.032	0.051	0.022
Porifera sp.47	–0.053	0.121	–0.170	–0.037	0.058	–0.007	–0.073
Porifera sp.49	–0.035	–0.127	0.424	0.176	–0.117	–0.046	0.022
Porifera sp.75/62	–0.233	0.096	–0.504	0.494	0.125	–0.241	–0.143
Porifera sp.121	–0.284	0.089	0.068	0.191	–0.100	–0.011	0.096
Porifera sp.123	–0.276	0.188	–0.152	0.267	–0.031	–0.012	–0.023
Cnidaria							
Alcyonarian sp.*sp.1*	0.103	–0.120	0.137	0.520	–0.061	0.070	0.185
Alcyonarian sp.*2*	–0.567	0.250	0.266	0.160	0.046	0.162	–0.008
Alcyonarian sp.*3*	0.685	0.094	–0.274	0.206	–0.014	0.103	0.072
Alcyonarian sp.*4*	0.386	–0.037	0.225	0.167	0.210	–0.036	0.021
Alcyonarian sp.*8*	0.105	0.278	0.273	0.262	0.421	0.033	0.100
Alcyonarian sp.*10*	0.759	–0.138	0.806	0.252	–0.008	0.207	0.011
Alcyonarian sp.*11*	0.092	–0.063	0.371	0.185	0.110	0.166	–0.149
Alcyonarian sp.*15*	0.080	–0.423	–1.339	0.030	0.114	–0.001	–0.088
Alcyonarian sp.*18*	0.142	0.068	0.221	0.130	0.164	0.064	0.043
Alcyonarian sp.*19*	–0.045	0.218	–0.313	0.230	0.097	–0.059	–0.032
Flabellum sp.	0.926	0.171	1.305	0.033	0.074	0.347	–0.068
Fungia sp.1	–2.259	1.219	–1.711	0.477	–0.274	–0.184	0.141
Fungia sp.3	–0.822	0.361	–0.044	0.170	–0.115	–0.140	0.058
Fungia sp.4	–0.429	0.248	–1.233	0.069	–0.147	–0.140	–0.026
Gorgonian sp.*3*	0.315	–0.229	–0.481	0.380	–0.001	0.063	–0.010
Hydroid sp.5	–0.228	–0.286	0.273	0.207	–0.042	–0.004	0.029
Hydroid sp.9	–0.857	0.068	–0.629	0.387	–0.195	–0.166	0.143
Sphaenopus sp.1	–0.746	0.851	–0.337	–0.146	–0.222	0.394	–0.123
Crustaceans							
Calappa sp.2	–0.205	0.065	0.114	0.009	0.010	0.021	0.004
Calappa terraereginae	1.210	–0.187	–0.433	–0.220	–0.129	–0.045	–0.052
Charybdis jaubertensis	0.083	0.012	–0.116	–0.094	0.034	0.043	–0.023
Cryptopodia sp.3	0.513	–0.801	–0.116	0.073	0.053	0.015	–0.081
Dardanus imbricata	–0.835	0.063	–0.602	–0.152	–0.109	0.072	–0.177
Diogenes sp.3	0.022	–0.122	–0.194	0.142	–0.306	–0.045	0.058
Dorippe frascone	0.225	0.117	–0.482	–0.110	0.080	0.082	–0.052
Hyastenus sp.1	–0.303	–0.023	0.060	0.088	–0.050	0.027	0.056
Hyastenus sp.4	0.111	0.454	–0.221	–0.096	0.027	0.129	–0.146
Ixa inermis	0.058	–0.066	0.172	–0.036	0.057	–0.021	0.004
Leucosia ocellata	0.475	–0.140	–0.143	0.016	0.180	–0.001	–0.148
Metapenaeopsis palmensis	0.332	–0.150	0.059	0.053	0.077	0.129	–0.086
Metapenaeus endeavouri	0.625	–0.221	–0.226	–0.013	–0.187	0.013	–0.029
Pagurid	–0.410	0.493	–1.407	0.335	0.034	–0.250	–0.121
Parthenope harpax	–0.035	–0.072	0.262	0.077	0.048	–0.026	–0.071
Parthenope hoplonotus	0.298	–0.481	0.243	0.103	0.083	0.012	–0.083

Species	mud	carbonate	depth	habitat	year	north vs south	closed vs open
Parthenope longimanus	0.664	–0.259	0.202	0.128	0.148	0.051	0.013
Parthenope longispinus	–0.088	–0.237	0.282	–0.004	0.026	0.010	0.008
Penaeus esculentus	0.786	0.207	–0.399	–0.183	–0.090	–0.069	0.119
Penaeus latisulcatus	–0.064	–0.223	–0.068	–0.004	–0.018	–0.029	–0.055
Penaeus longistylus	0.213	–0.166	0.242	0.010	0.032	0.059	–0.067
Phalangipes australiensis	–0.173	–0.172	0.554	0.032	0.035	0.120	–0.156
Phalangipes longipes	0.351	0.112	0.170	0.066	–0.067	0.015	0.027
Pilumnus semilanatus	0.045	0.039	–0.037	0.286	–0.041	–0.045	0.003
Pilumnus sp.1	–0.129	0.020	0.184	0.216	–0.021	–0.042	–0.093
Portunus gracilimanus	0.857	–0.153	0.275	–0.320	–0.077	–0.127	0.031
Portunus pelagicus	–0.050	–0.171	–0.074	–0.035	–0.053	0.021	–0.035
Portunus rubromarginatus	0.591	0.273	–0.251	–0.226	0.192	0.198	–0.147
Portunus tenuipes	1.140	0.358	–0.326	–0.130	0.003	0.248	–0.052
Scyllarus demani	–0.068	–0.094	–0.196	–0.201	0.065	0.157	–0.120
Spiropagurus sp.3	0.084	–0.006	0.034	–0.064	–0.141	–0.079	–0.095
Thalamita sima	0.415	0.188	–0.297	0.217	–0.069	0.103	0.025
Thenus orientalis	0.297	0.491	–0.232	–0.194	–0.031	0.014	0.005
Trachypenaeus granulosus	0.403	–0.072	0.248	–0.043	–0.035	0.040	–0.003
Molluscs							
Amusium pleuronectes	2.045	–0.594	0.091	0.191	0.094	0.161	0.038
Annachlamys flabellata	0.260	–0.490	0.089	0.108	–0.057	0.051	0.036
Antigonia lamellaris	1.043	–0.332	0.229	0.277	0.072	0.157	–0.046
Arca navicularis	–0.020	–0.615	0.554	0.004	–0.116	0.006	0.116
Barbatia foliata	0.115	0.064	0.021	0.115	–0.099	0.027	0.062
Bassina calophylla	1.736	0.607	–0.366	–0.356	–0.125	–0.028	0.069
Bursa rana	0.326	–0.033	–0.142	–0.200	–0.066	–0.066	–0.062
Chicoreus banksii	–0.357	0.063	–0.228	0.280	–0.197	–0.100	0.039
Chicoreus cervicornis	1.485	–0.064	0.558	0.207	–0.148	0.285	–0.011
Circe scripta	0.078	0.050	–0.129	–0.032	0.001	0.048	0.035
Cronia contracta	–0.088	0.163	–0.171	0.141	–0.125	0.005	0.112
Ctenocardia virgo	–0.211	0.136	–0.402	0.083	0.007	–0.108	–0.099
Cucullaea labiata	0.898	0.383	–0.021	0.034	–0.060	0.018	0.087
Cymbiola sophia	0.331	–0.445	0.494	0.070	0.018	0.214	–0.041
Dendostraea folium	–0.011	–0.081	–0.082	–0.036	–0.164	0.006	0.018
Distorsio reticularis	–0.154	0.250	0.181	–0.183	–0.001	0.132	–0.050
Dosinia altenai	1.237	0.381	–0.057	–0.221	–0.067	0.015	–0.013
Dosinia juvinilis	0.202	0.163	–0.126	–0.120	0.006	0.064	–0.037
Echelus atratus	–0.254	–0.098	–0.468	–0.046	–0.047	0.047	0.059
Fragum retusum	–0.232	0.377	–0.850	–0.078	–0.092	–0.048	–0.035
Hyatina hyotis	0.399	–0.412	–0.168	0.224	–0.161	0.092	0.183
Lophiotoma indica	–0.233	0.262	–0.305	0.136	–0.027	0.001	–0.102
Malleus albus	0.458	–0.239	–0.304	0.180	–0.076	0.069	0.021
Melaxinia vitrea	1.320	0.339	0.215	–0.118	0.296	0.186	–0.145
Modiolus ostentatus	0.504	–0.120	–0.149	–0.034	–0.179	0.060	0.134
Murex macgillivrayi	0.373	–0.004	–0.317	0.006	–0.063	0.101	–0.037
Paphia semirugata	0.587	–0.123	–0.092	0.045	–0.007	0.108	–0.115
Pinctada fucata	–0.551	–0.259	–0.329	0.138	–0.084	–0.015	0.144
Placuna lincolni	0.387	0.085	0.091	0.138	–0.024	–0.028	–0.031
Plicatula essingtonensis	0.415	0.104	–0.024	–0.000	–0.176	0.127	–0.054
Pteria zebra	–0.079	–0.291	–0.176	0.065	–0.206	0.112	–0.051
Sepioidea sp.1	0.650	0.199	–0.204	–0.127	–0.091	0.134	0.081
Sepioidea sp.2	0.259	0.205	–0.143	0.017	0.085	0.051	–0.071
Sepioidea sp.3	–0.013	–0.024	0.167	0.027	0.105	–0.084	–0.111
Spondylus wrightianus	0.561	–0.255	0.798	0.001	0.009	0.058	0.038
Strombus diliatus	–0.185	0.260	–0.324	0.060	–0.017	0.007	–0.090
Strombus vittatus	0.208	–0.109	–0.489	0.015	–0.238	0.158	–0.173
Trisidos semitorta	0.626	0.182	–0.149	–0.203	–0.011	0.023	0.109
Vepricardium multispinosum	0.839	0.211	–0.167	–0.066	–0.199	0.006	–0.016

Species	mud	carbonate	depth	habitat	year	north vs south	closed vs open
Volva volva	–0.191	–0.025	0.200	–0.063	0.108	0.008	0.049
Xenophora solarioides	–0.212	–0.319	0.654	–0.110	–0.071	0.027	–0.052
Bryozoans							
Amathia sp.	–0.119	–0.065	0.055	0.062	0.126	0.084	0.000
Bryozoan sp.2	–0.259	0.099	–0.193	0.220	–0.109	–0.084	–0.060
Bryozoan sp.3	–0.109	–0.065	–0.053	–0.015	0.151	0.027	–0.000
Bryozoan sp.6	0.086	–0.060	0.370	0.440	–0.599	0.141	0.157
Bryozoan sp.8	–0.165	0.447	–0.399	0.129	–0.062	–0.054	–0.213
Bryozoan sp.9	–0.839	–0.072	–0.145	0.078	–0.085	–0.111	0.056
Bryozoan sp.18	–0.130	0.027	0.210	0.251	–0.164	0.017	0.125
Bryozoan sp.23	–0.806	0.426	0.259	0.333	–0.400	0.067	0.144
Retiflustia cornea	–0.261	–0.163	0.207	0.087	0.136	0.077	0.021
Scrupocellaria sp.	–0.557	–0.410	0.154	0.304	–0.230	0.007	0.260
Triphyllozoon sp.	–0.691	0.394	0.013	0.091	–0.056	0.018	–0.038
Echinoderms							
Asteroid (mixed spp.)	0.016	0.109	–0.233	–0.184	–0.088	0.156	–0.178
Asteroid sp.11	–0.081	–0.027	0.580	–0.009	0.122	0.034	0.089
Astropecten granulatus	1.375	0.283	–0.372	0.035	0.138	0.004	–0.009
Astropecten sp.4	1.531	–0.289	0.706	0.316	0.179	0.179	–0.025
Brissopsis sp.2	1.860	–0.506	0.540	–0.041	0.038	–0.092	–0.055
Brissopsis sp.ss	0.379	–0.129	–0.158	–0.054	–0.062	0.035	0.057
Crinoid sp.12	–0.333	0.101	0.158	0.106	–0.144	–0.086	0.048
Crinoid sp.15	–2.083	1.054	–0.059	0.237	0.078	0.115	0.117
Crinoid sp.16	0.041	0.231	–0.468	–0.020	0.097	–0.036	–0.027
Crinoid sp.17	–2.255	1.345	0.214	0.199	–0.198	0.061	0.189
Crinoid sp.19	–1.208	0.672	0.110	0.049	–0.125	–0.040	0.187
Crinoid sp.21	0.501	0.226	0.520	–0.040	0.100	0.107	0.083
Crinoid sp.22	–0.233	0.292	–0.103	0.133	–0.058	–0.059	–0.041
Crinoid sp.26	–0.421	0.436	–0.161	0.020	0.000	0.064	–0.100
Crinoid sp.27	–1.140	0.752	–0.613	0.436	–0.216	–0.240	0.018
Crinoid sp.5	–1.879	0.898	–0.482	0.399	–0.336	–0.257	0.273
Crinoidea	–0.385	0.024	0.265	–0.033	0.054	0.177	–0.031
Echinoid sp.3	0.026	–0.033	0.304	–0.021	–0.002	–0.032	–0.008
Echinoid sp.6	–0.093	–0.006	0.093	0.148	0.025	0.040	–0.095
Euretaster insignis	0.057	–0.219	0.363	–0.048	0.221	–0.080	–0.036
Gorgonocephalid sp.1	–0.796	0.075	1.054	0.106	–0.034	0.014	0.167
Holothuria ocellata	1.043	–0.266	–0.515	0.171	0.068	0.100	0.037
Holothurian sp.3	–0.303	0.229	–0.173	0.029	–0.035	–0.026	0.009
Holothurian sp.38	–0.468	0.524	–0.758	–0.132	–0.273	–0.095	–0.111
Iconaster longimanus	–0.119	0.129	0.535	0.148	0.165	0.234	0.045
Laganum sp.2	0.146	–0.172	–0.625	–0.147	0.195	0.040	–0.148
Laganum sp.3	2.091	0.108	–1.200	0.261	0.373	0.172	–0.125
Laganum sp.8	2.301	–0.446	0.785	0.309	0.221	0.350	0.106
Luidia maculata	–0.204	0.099	0.528	–0.129	0.037	0.002	0.013
Maretia ovata	2.094	0.396	0.642	0.106	–0.277	–0.143	0.139
Metrodira subulata	0.364	–0.038	0.330	0.295	0.169	0.328	0.112
Ophiuroid sp.1	–0.547	0.021	0.341	0.012	–0.092	0.005	–0.025
Ophiuroid sp.34	–1.142	0.285	0.278	0.486	–0.038	–0.009	0.222
Ophiuroid sp.5	–0.067	0.046	0.252	0.136	0.177	0.069	0.049
Pentaceraster sp.	–0.233	–0.024	–0.239	0.114	–0.051	–0.034	0.086
Pentacta anceps	0.852	0.606	–0.564	–0.109	–0.001	0.051	0.202
Prionocidaris sp.2	0.065	0.269	0.578	0.098	–0.241	0.162	–0.291
Stellaster equestris	0.594	0.309	–1.185	0.213	0.410	0.427	0.078
Ascidians							
Ascidia scaevola	–0.142	0.115	0.045	0.160	0.100	–0.091	0.021
Ascidia sydneiensis	0.888	–0.075	–0.637	–0.142	–0.009	0.042	0.151
Ascidian sp.1	1.149	0.091	–0.138	0.087	–0.178	0.120	0.093
Cemidocarpa stolonifera	–0.193	0.057	0.263	–0.024	–0.085	0.022	0.028

Species	**mud**	**carbonate**	**depth**	**habitat**	**year**	**north vs south**	**closed vs open**
Herdmania momus	0.792	–0.352	0.285	0.454	0.128	0.280	0.103
Hypodistoma deerratum	–0.522	–0.483	0.768	0.335	–0.110	0.002	0.038
Microcosmus exasperatus	–0.007	0.241	–0.666	–0.084	0.001	–0.056	0.066
Microcosmus helleri	0.256	–0.409	0.458	0.045	–0.412	0.078	–0.137
Phallusia millari	1.329	0.197	–0.023	–0.090	0.082	0.234	0.072
Polycarpa chinensis	0.468	–0.098	0.231	0.012	–0.192	–0.029	0.100
Polycarpa papillata	0.008	–0.355	–0.479	0.075	0.075	0.193	0.004
Pseudodistoma sp.	0.523	0.013	0.362	0.177	–0.071	0.035	–0.021
Pyura sacciformis	0.355	0.058	0.307	0.030	0.034	–0.007	0.124
Rhopalaea tenuis	–0.021	–0.407	–0.410	0.011	–0.178	–0.025	0.083

Table App.3.D.3 Significance level for log-transformed number for benthic invertebrate species present in at least 11 hauls.

Species	*f*	mud	carbonate	depth	habitat	year	north vs south	closed vs open
Sponges								
Club sponge 1	20	.141	.310	.497	.233	.242	.334	.414
Ianthella sp.	13	.446	.986	.562	.015	.924	.174	.260
Porifera	24	.090	.994	.820	.946	.121	.390	.499
Porifera sp.8	11	.675	.272	.023	.006	.231	<.001	.019
Porifera sp.10	59	.288	.956	.122	.001	.009	.265	.366
Porifera sp.14	15	.158	.265	.995	.004	.527	.316	.853
Porifera sp.18	21	.003	.209	.993	.252	.007	.596	.255
Porifera sp.36	40	.002	.724	.521	<.001	.610	.206	.800
Porifera sp.42	26	.011	.089	.359	.001	.155	.002	.763
Porifera sp.46	14	.099	.039	.952	.032	.433	.106	.560
Porifera sp.47	11	.586	.300	.237	.424	.289	.603	.108
Porifera sp.49	24	.895	.436	.014	.478	.274	.068	.728
Porifera sp.75/62	20	.251	.896	.127	<.001	.327	.001	.175
Porifera sp.121	12	.011	.562	.530	.024	.020	.787	.045
Porifera sp.123	12	.068	.373	.600	.015	.702	.812	.988
Cnidaria								
Alcyonarian sp.1	63	.933	.641	.549	.011	.764	.343	.116
Alcyonarian sp.2	20	.025	.310	.433	.266	.630	.031	.921
Alcyonarian sp.3	43	.002	.834	.459	.092	.698	.125	.789
Alcyonarian sp.4	39	.179	.871	.274	.337	.005	.872	.806
Alcyonarian sp.8	35	.618	.294	.421	.254	<.001	.679	.155
Alcyonarian sp.10	41	<.001	.477	.012	.302	.595	.029	.794
Alcyonarian sp.11	43	.869	.966	.323	.169	.876	.009	.097
Alcyonarian sp.15	33	.948	.458	<.001	.864	.609	.462	.114
Alcyonarian sp.18	12	.386	.620	.147	.181	.001	.102	.380
Alcyonarian sp.19	14	.829	.129	.043	.008	.111	.131	.496
Flabellum sp.	63	<.001	.606	.001	.823	.483	<.001	.468
Fungia sp.1	64	<.001	.001	<.001	.050	.032	.096	.391
Fungia sp.3	16	<.001	.139	.926	.272	.198	.055	.517
Fungia sp.4	18	.044	.292	<.001	.348	.094	.034	.450
Gorgonian 3	21	.071	.527	.049	.003	.576	.476	.538
Hydroid sp.5	22	.096	.087	.285	.084	.324	.972	.475
Hydroid sp.9	52	<.001	.930	.450	.039	.280	.142	.248
Sphaenopus sp.1	123	<.001	.003	.606	.702	.089	.001	.232
Crustaceans								
Calappa sp.2	11	.004	.452	.356	.780	.801	.487	.986
Calappa terraereginae	49	<.001	.418	.382	.603	.515	.803	.826
Charybdis jaubertensis	12	.387	.852	.249	.131	.273	.126	.459
Cryptopodia sp.3	30	.030	.008	.771	.908	.866	.789	.257
Dardanus imbricata	42	.001	.714	.042	.645	.283	.535	.131
Diogenes sp.3	20	.595	.501	.508	.029	<.001	.485	.256
Dorippe frascone	34	.127	.709	.047	.187	.194	.120	.480
Hyastenus sp.1	12	.002	.927	.558	.161	.222	.506	.138
Hyastenus sp.4	23	.897	.072	.480	.922	.491	.240	.103
Ixa inermis	14	.463	.553	.158	.359	.282	.388	.750
Leucosia ocellata	35	.001	.393	.493	.970	.024	.992	.024
Metapenaeopsis palmensis	41	.081	.670	.846	.719	.263	.032	.205
Metapenaeus endeavouri	27	.003	.186	.180	.924	.021	.670	1.000
Pagurid	11	.088	.104	<.001	.044	.776	.005	.349
Parthenope harpax	25	.755	.538	.146	.539	.585	.447	.273
Parthenope hoplonotus	26	.024	<.001	.112	.170	.219	.811	.255
Parthenope longimanus	39	<.001	.137	.318	.202	.015	.264	.852
Parthenope longispinus	14	.430	.163	.221	.982	.642	.636	.963

Species	*f*	mud	carbonate	depth	habitat	year	north vs south	closed vs open
Penaeus esculentus	33	<.001	.568	.060	.269	.124	.259	.094
Penaeus latisulcatus	11	.493	.015	.461	.840	.421	.478	.164
Penaeus longistylus	17	.150	.334	.380	.845	.624	.163	.452
Phalangipes australiensis	25	.412	.538	.051	.659	.734	.097	.147
Phalangipes longipes	15	<.001	.170	.406	.441	.134	.490	.609
Pilumnus semilanatus	11	.675	.748	.999	.006	.198	.191	.722
Pilumnus sp.1	17	.412	.996	.502	.053	.520	.582	.478
Portunus gracilimanus	41	<.001	.247	.102	.010	.039	.006	.738
Portunus pelagicus	11	.649	.153	.084	.371	.100	.907	.846
Portunus rubromarginatus	81	.116	.252	.685	.491	.211	.040	.178
Portunus tenuipes	69	<.001	.184	.449	.546	.911	.004	.524
Scyllarus demani	21	.622	.726	.290	.033	.230	<.001	.025
Spiropagurus sp.3	15	.496	.517	.408	.215	<.001	.007	.023
Thalamita sima	13	.113	.369	.394	.133	.277	.262	.581
Thenus orientalis	23	.113	.048	.203	.214	.468	.895	.668
Trachypenaeus granulosus	24	.001	.545	.213	.673	.628	.208	.945
Molluscs								
Amusium pleuronectes	70	<.001	.119	.659	.394	.534	.198	.900
Annachlamys flabellata	22	.028	.003	.653	.272	.893	.196	.988
Antigonia lamellaris	47	<.001	.078	.296	.035	.638	.010	.351
Arca navicularis	18	.869	.002	.015	.963	.061	.901	.276
Barbatia foliata	12	.208	.788	.769	.159	.042	.704	.134
Bassina calophylla	53	<.001	.013	.310	.041	.180	.816	.419
Bursa rana	23	.007	.834	.511	.023	.210	.102	.158
Chicoreus banksii	13	.002	.814	.301	.002	.001	.024	.339
Chicoreus cervicornis	65	<.001	.910	.053	.184	.084	<.001	.636
Circe scripta	12	.421	.679	.477	.643	.632	.122	.469
Cronia contracta	12	.580	.277	.443	.058	.017	.827	.043
Ctenocardia virgo	13	.087	.431	.052	.243	.953	.006	.031
Cucullaea labiata	26	<.001	.071	.931	.433	.352	.761	.307
Cymbiola sophia	46	.028	.049	.047	.523	.808	<.001	.385
Dendostraea folium	11	.421	.709	.307	.789	<.001	.517	.998
Distorsio reticularis	19	.182	.132	.408	.077	.885	.004	.319
Dosinia altenai	44	<.001	.077	.779	.206	.547	.639	.854
Dosinia juvinilis	14	.081	.337	.753	.224	.894	.093	.395
Echelus atratus	14	.039	.395	.029	.612	.577	.208	.455
Fragum retusum	20	.046	.011	<.001	.446	.136	.420	.532
Hyatina hyotis	26	.022	.296	.489	.073	.078	.154	.098
Lophiotoma indica	18	.205	.125	.126	.133	.481	.906	.139
Malleus albus	29	.031	.093	.813	.203	.343	.364	.810
Melaxinia vitrea	66	<.001	.261	.444	.784	<.001	.009	.139
Modiolus ostentatus	18	<.001	.650	.933	.829	.004	.163	.070
Murex macgillivrayi	24	.009	.850	.216	.668	.270	.109	.633
Paphia semirugata	29	<.001	.544	.686	.707	.986	.024	.054
Pinctada fucata	11	.003	.303	.350	.092	.038	.606	.065
Placuna lincolni	16	.002	.861	.164	.041	.227	.516	.536
Plicatula essingtonensis	26	.015	.817	.612	.827	.016	.035	.444
Pteria zebra	15	.541	.130	.545	.434	.001	.009	.293
Sepioidea sp.1	24	<.001	.345	.339	.555	.293	.068	.369
Sepioidea sp.2	23	.261	.060	.164	.991	.445	.324	.230
Sepioidea sp.3	11	.952	.713	.900	.475	.013	.005	.004
Spondylus wrightianus	32	.012	.102	.002	.816	.642	.841	.541
Strombus diliatus	19	.173	.121	.119	.675	.892	.984	.250
Strombus vittatus	55	.459	.723	.166	.968	.017	.027	.081
Trisidos semitorta	22	<.001	.287	.651	.066	.790	.420	.193
Vepricardium multispinosum	31	<.001	.294	.428	.647	.006	.514	.847
Volva volva	18	.118	.861	.201	.397	.013	.813	.564
Xenophora solarioides	35	.267	.137	.024	.620	.913	.392	.377

Species	*f*	mud	carbonate	depth	habitat	year	north vs south	closed vs open
Bryozoans								
Amathia sp.	13	.162	.893	.692	.696	.032	.050	.994
Bryozoan sp.2	11	.023	.667	.504	.016	.075	.088	.529
Bryozoan sp.3	21	.419	.781	.851	.786	.031	.402	.655
Bryozoan sp.6	32	.772	.410	.201	.003	<.001	.072	.051
Bryozoan sp.8	17	.161	.108	.501	.193	.152	.493	.132
Bryozoan sp.9	34	<.001	.755	.847	.630	.278	.092	.426
Bryozoan sp.18	14	.189	.823	.251	.008	.001	.639	.043
Bryozoan sp.23	34	<.001	.214	.528	.048	<.001	.668	.241
Retiflustia cornea	27	.126	.530	.523	.616	.124	.096	.993
Scrupocellaria sp.	20	.002	.124	.631	.014	.001	.739	.001
Triphyllozoon sp.	32	.001	.147	.981	.438	.136	.884	.835
Echinoderms								
Asteroid (mixed spp.)	19	.634	.824	.279	.178	.016	.023	.045
Asteroid sp.11	11	.281	.619	.005	.539	.181	.411	.200
Astropecten granulatus	79	<.001	.253	.701	.929	.072	.872	.657
Astropecten sp.4	61	<.001	.317	.039	.079	.060	.027	.771
Brissopsis sp.2	57	<.001	.199	.235	.471	.591	.210	.590
Brissopsis sp.ss	18	.002	.967	.776	.683	.909	.207	.661
Crinoid sp.12	13	.012	.430	.456	.356	.034	.079	.328
Crinoid sp.15	63	<.001	.006	.979	.257	.533	.610	.368
Crinoid sp.16	14	.973	.280	.036	.826	.469	.426	.595
Crinoid sp.17	77	<.001	<.001	.694	.130	.202	.880	.120
Crinoid sp.19	45	<.001	.009	.605	.772	.315	.364	.018
Crinoid sp.21	21	.003	.316	.016	.828	.216	.036	.339
Crinoid sp.22	28	.161	.305	.578	.289	.152	.144	.757
Crinoid sp.26	23	.014	.096	.696	.733	.135	.622	.232
Crinoid sp.27	39	<.001	.030	.165	.007	.013	.002	.696
Crinoid sp.5	62	<.001	.001	.238	.042	.025	.002	.043
Crinoidea	13	.348	.445	.997	.239	.019	.046	.090
Echinoid sp.3	13	.835	.453	.009	.918	.796	.329	.591
Echinoid sp.6	17	.481	.980	.752	.104	.858	.874	.125
Euretaster insignis	21	.780	.136	.052	.886	.116	.053	.584
Gorgonocephalid sp.1	28	<.001	.791	.001	.509	.200	.925	.311
Holothuria ocellata	47	<.001	.327	.255	.131	.536	.113	.763
Holothurian sp.3	11	.007	.068	.200	.676	.527	.205	.986
Holothurian sp.38	22	.048	.076	.024	.789	.016	.314	.270
Iconaster longimanus	34	.360	.556	.012	.139	.028	<.001	.237
Laganum sp.2	44	.625	.774	.066	.354	.205	.840	.124
Laganum sp.3	86	<.001	.571	.050	.073	.178	.489	.907
Laganum sp.8	55	<.001	.364	.074	.137	.192	.004	.373
Luidia maculata	12	.415	.492	.056	.339	.535	.984	.764
Maretia ovata	35	<.001	.305	.226	.546	.113	.241	.334
Metrodira subulata	66	.616	.924	.317	.193	.387	.002	.899
Ophiuroid sp.1	52	.017	.896	.167	.919	.612	.844	.623
Ophiuroid sp.34	30	<.001	.285	.332	.001	.457	.840	.011
Ophiuroid sp.5	15	.576	.718	.168	.116	.002	.065	.314
Pentaceraster sp.	13	.011	.850	.077	.092	.216	.194	.077
Pentacta anceps	43	.002	.092	.311	.716	.259	.765	.129
Prionocidaris sp.2	29	.803	.527	.147	.442	.050	.240	.094
Stellaster equestris	94	.218	.416	.064	.409	.036	.001	.674
Ascidians								
Ascidia scaevola	23	.800	.653	.589	.106	.164	.131	.605
Ascidia sydneiensis	37	<.001	.887	.021	.241	.573	.379	.046
Ascidian sp.1	38	<.001	.627	.903	.490	.037	.051	.211
Cemidocarpa stolonifera	14	.098	.768	.147	.680	.173	.700	.641
Herdmania momus	42	<.001	.178	.444	.007	.247	<.001	.274
Hypodistoma deerratum	32	.070	.194	.098	.108	.362	.973	.444

Species	***f***	**mud**	**carbonate**	**depth**	**habitat**	**year**	**north vs south**	**closed vs open**
Microcosmus exasperatus	19	.896	.112	.001	.352	.794	.187	.200
Microcosmus helleri	19	.128	.172	.219	.516	<.001	.167	.124
Phallusia millari	60	<.001	.734	.557	.511	.818	.003	.396
Polycarpa chinensis	32	.030	.455	.358	.917	.022	.531	.316
Polycarpa papillata	38	.869	.207	.348	.455	.432	.028	.832
Pseudodistoma sp.	28	.001	.860	.143	.179	.983	.356	.777
Pyura sacciformis	19	.001	.679	.099	.685	.471	.929	.025
Rhopalaea tenuis	18	.907	.021	.118	.803	.012	.502	.178

Table App.3.D.4 Estimated coefficient for log-transformed number for benthic invertebrate species present in at least 11 hauls.

Species	mud	carbonate	depth	habitat	year	north vs south	open vs closed
Sponges							
Club sponge 1	0.151	0.127	–0.112	0.096	0.057	0.035	0.039
Ianthella sp.	–0.054	0.001	0.066	0.138	–0.003	–0.035	–0.038
Porifera	0.157	0.001	0.033	–0.005	–0.067	0.028	–0.029
Porifera sp.8	–0.032	0.104	–0.284	0.171	0.044	–0.101	–0.086
Porifera sp.10	–0.178	0.011	0.417	0.445	–0.210	–0.067	0.071
Porifera sp.14	–0.147	–0.141	–0.001	0.240	–0.031	–0.037	–0.009
Porifera sp.18	0.239	–0.120	0.001	–0.071	–0.100	0.015	0.042
Porifera sp.36	0.306	–0.041	–0.098	0.589	–0.023	0.043	–0.011
Porifera sp.42	–0.343	0.279	–0.198	0.365	–0.090	–0.150	0.019
Porifera sp.46	0.120	–0.183	–0.007	0.123	–0.027	0.042	0.020
Porifera sp.47	–0.037	0.086	–0.130	–0.043	0.034	–0.013	–0.052
Porifera sp.49	–0.014	–0.104	0.433	0.061	–0.056	–0.071	0.018
Porifera sp.75/62	–0.157	0.022	–0.337	0.437	0.063	–0.168	–0.087
Porifera sp.121	–0.258	0.071	0.101	0.180	–0.111	–0.010	0.095
Porifera sp.123	–0.248	0.147	–0.114	0.260	–0.024	–0.012	0.001
Cnidaria							
Alcyonarian sp.*1*	–0.017	–0.115	0.195	0.408	–0.029	0.069	0.150
Alcyonarian sp.*2*	–0.247	0.135	0.138	0.096	0.025	0.085	–0.005
Alcyonarian sp.*3*	0.430	0.035	–0.165	0.185	0.026	0.076	0.017
Alcyonarian sp.*4*	0.195	–0.029	0.255	0.109	0.195	–0.008	0.017
Alcyonarian sp.*8*	0.075	0.193	0.195	0.136	0.298	0.022	0.101
Alcyonarian sp.*10*	0.439	–0.103	0.489	0.097	–0.030	0.094	–0.015
Alcyonarian sp.*11*	0.020	0.006	0.197	0.135	0.009	0.118	–0.097
Alcyonarian sp.*15*	–0.006	–0.089	–0.735	0.013	0.024	–0.026	–0.073
Alcyonarian sp.*18*	0.088	0.061	0.236	0.107	0.157	0.059	0.042
Alcyonarian sp.*19*	–0.024	0.209	–0.369	0.236	0.085	–0.061	–0.036
Flabellum sp.	0.679	0.115	1.014	0.032	0.061	0.281	–0.062
Fungia sp.1	–1.893	1.029	–1.526	0.387	–0.255	–0.149	0.101
Fungia sp.3	–0.818	0.356	–0.029	0.171	–0.120	–0.136	0.060
Fungia sp.4	–0.320	0.203	–1.128	0.117	–0.126	–0.120	–0.056
Gorgonian sp.*3*	0.183	–0.078	–0.320	0.236	0.027	0.026	–0.029
Hydroid sp.5	–0.219	–0.275	0.226	0.179	–0.061	–0.002	0.044
Hydroid sp.9	–0.713	0.021	–0.238	0.322	–0.100	–0.103	0.107
Sphaenopus sp.1	–1.047	1.037	–0.231	–0.084	–0.225	0.328	–0.157
Crustaceans							
Calappa sp.2	–0.161	0.051	0.082	0.012	0.007	0.014	–0.000
Calappa terraereginae	0.569	–0.117	–0.167	–0.049	–0.037	–0.011	–0.012
Charybdis jaubertensis	0.049	0.013	–0.105	–0.068	0.029	0.031	–0.020
Cryptopodia sp.3	0.190	–0.282	–0.041	0.008	0.007	–0.008	–0.046
Dardanus imbricata	–0.485	0.064	–0.469	–0.052	–0.072	0.032	–0.101
Diogenes sp.3	–0.049	–0.075	–0.098	0.159	–0.202	–0.023	0.049
Dorippe frascone	0.168	0.050	–0.351	–0.114	0.067	0.061	–0.036
Hyastenus sp.1	–0.273	0.009	0.080	0.094	–0.049	0.020	0.059
Hyastenus sp.4	–0.014	0.237	–0.122	–0.008	0.035	0.045	–0.083
Ixa inermis	0.043	–0.043	0.134	–0.043	0.030	–0.018	0.009
Leucosia ocellata	0.390	–0.121	–0.128	0.003	0.125	–0.000	–0.124
Metapenaeopsis palmensis	0.240	–0.071	0.043	0.039	0.072	0.106	–0.082
Metapenaeus endeavouri	0.266	–0.143	–0.191	0.007	–0.097	0.013	–0.000
Pagurid	–0.200	0.232	–0.678	0.187	0.016	–0.119	–0.051
Parthenope harpax	–0.033	–0.081	0.252	0.052	0.028	–0.029	–0.055
Parthenope hoplonotus	0.197	–0.437	0.222	0.094	0.050	0.007	–0.046
Parthenope longimanus	0.478	–0.188	0.166	0.104	0.120	0.041	0.009
Parthenope longispinus	–0.062	–0.135	0.156	0.001	0.017	0.013	0.002

Species	mud	carbonate	depth	habitat	year	north vs south	open vs closed
Penaeus esculentus	0.495	0.074	–0.324	–0.093	–0.078	–0.043	0.084
Penaeus latisulcatus	–0.043	–0.189	–0.074	0.010	–0.024	–0.016	–0.041
Penaeus longistylus	0.103	–0.084	0.100	0.011	0.016	0.035	–0.025
Phalangipes australiensis	–0.084	–0.076	0.321	0.035	0.016	0.061	–0.069
Phalangipes longipes	0.298	0.124	0.099	0.045	–0.052	0.018	0.018
Pilumnus semilanatus	–0.027	0.025	–0.000	0.143	–0.039	–0.030	0.011
Pilumnus sp.1	–0.085	–0.001	0.111	0.158	–0.031	–0.020	–0.034
Portunus gracilimanus	0.550	–0.146	0.273	–0.211	–0.102	–0.103	0.016
Portunus pelagicus	–0.022	–0.084	–0.134	–0.034	–0.038	0.002	–0.004
Portunus rubromarginatus	0.257	0.228	–0.106	–0.088	0.097	0.121	–0.103
Portunus tenuipes	0.923	0.314	–0.235	–0.092	–0.010	0.199	–0.058
Scyllarus demani	–0.037	–0.032	–0.127	–0.126	0.042	0.102	–0.079
Spiropagurus sp.3	0.044	–0.051	0.086	–0.063	–0.113	–0.063	–0.069
Thalamita sima	0.131	0.090	–0.113	0.098	–0.042	0.033	0.021
Thenus orientalis	0.138	0.210	–0.178	–0.085	–0.030	0.004	0.017
Trachypenaeus granulosus	0.315	–0.067	0.183	–0.030	–0.021	0.041	–0.003
Molluscs							
Amusium pleuronectes	1.396	–0.320	0.119	0.113	0.049	0.077	–0.010
Annachlamys flabellata	0.154	–0.261	0.050	0.061	–0.004	0.032	–0.001
Antigonia lamellaris	0.584	–0.239	0.186	0.185	0.025	0.104	–0.049
Arca navicularis	–0.012	–0.268	0.275	0.003	–0.062	–0.003	0.036
Barbatia foliata	0.115	0.030	0.043	0.102	–0.088	0.012	0.064
Bassina calophylla	1.438	0.504	–0.270	–0.268	–0.105	–0.014	0.063
Bursa rana	0.198	–0.018	–0.076	–0.130	–0.043	–0.042	–0.048
Chicoreus banksii	–0.359	0.033	–0.191	0.288	–0.186	–0.093	0.052
Chicoreus cervicornis	1.253	–0.023	0.530	0.178	–0.139	0.253	–0.038
Circe scripta	0.052	0.033	–0.074	–0.024	0.015	0.036	0.022
Cronia contracta	–0.045	0.107	–0.099	0.121	–0.092	0.006	0.077
Ctenocardia virgo	–0.143	0.080	–0.261	0.076	0.002	–0.083	–0.085
Cucullaea labiata	0.498	0.190	0.012	0.053	–0.038	0.009	0.041
Cymbiola sophia	0.249	–0.272	0.361	0.056	0.013	0.161	–0.046
Dendostraea folium	–0.069	–0.039	–0.140	–0.018	–0.143	–0.020	0.000
Distorsio reticularis	–0.112	0.154	0.111	–0.117	–0.006	0.087	–0.039
Dosinia altenai	0.982	0.297	–0.062	–0.137	–0.039	0.023	–0.012
Dosinia juvinilis	0.126	0.084	–0.036	–0.069	0.005	0.043	–0.029
Echelus atratus	–0.186	–0.093	–0.316	–0.036	–0.024	0.040	0.031
Fragum retusum	–0.212	0.330	–0.754	–0.063	–0.075	–0.030	–0.031
Hyatina hyotis	0.242	–0.133	–0.116	0.148	–0.087	0.053	0.081
Lophiotoma indica	–0.136	0.200	–0.263	0.127	–0.036	–0.004	–0.074
Malleus albus	0.235	–0.223	0.041	0.109	–0.049	0.035	0.012
Melaxinia vitrea	0.947	0.224	0.200	–0.035	0.277	0.153	–0.113
Modiolus ostentatus	0.305	–0.039	–0.009	–0.012	–0.097	0.035	0.060
Murex macgillivrayi	0.231	–0.020	–0.174	0.030	–0.046	0.050	–0.020
Paphia semirugata	0.370	–0.068	–0.060	0.027	0.001	0.075	–0.083
Pinctada fucata	–0.395	–0.162	–0.194	0.172	–0.127	–0.024	0.112
Placuna lincolni	0.265	0.018	0.193	0.139	–0.049	–0.020	–0.025
Plicatula essingtonensis	0.260	0.030	0.086	0.018	–0.121	0.080	–0.038
Pteria zebra	–0.061	–0.184	–0.097	0.061	–0.160	0.094	–0.049
Sepioidea sp.1	0.306	0.099	–0.131	–0.040	–0.043	0.056	0.036
Sepioidea sp.2	0.093	0.190	–0.185	–0.001	0.030	0.029	–0.047
Sepioidea sp.3	0.003	0.025	–0.011	0.031	0.065	–0.056	–0.076
Spondylus wrightianus	0.299	–0.235	0.600	0.022	–0.026	–0.008	–0.034
Strombus diliatus	–0.160	0.222	–0.295	0.039	–0.008	–0.001	–0.063
Strombus vittatus	0.131	–0.076	–0.395	0.006	–0.201	0.141	–0.145
Trisidos semitorta	0.265	0.080	–0.044	–0.089	–0.008	0.018	0.037
Vepricardium multispinosum	0.633	0.128	–0.127	–0.036	–0.132	0.023	–0.009
Volva volva	–0.117	0.016	0.154	–0.050	0.089	0.006	0.020
Xenophora solarioides	–0.137	–0.223	0.450	–0.048	0.006	0.038	–0.051
Bryozoans							

Species	**mud**	**carbonate**	**depth**	**habitat**	**year**	**north vs south**	**open vs closed**
Amathia sp.	–0.106	–0.012	0.048	0.023	0.077	0.053	–0.000
Bryozoan sp.2	–0.296	0.068	–0.139	0.248	–0.110	–0.079	–0.038
Bryozoan sp.3	–0.076	–0.032	–0.028	–0.020	0.097	0.028	0.020
Bryozoan sp.6	–0.036	–0.126	0.258	0.295	–0.377	0.081	0.115
Bryozoan sp.8	–0.164	0.229	–0.126	0.120	–0.079	–0.029	–0.082
Bryozoan sp.9	–0.645	–0.058	–0.048	0.058	–0.079	–0.093	0.057
Bryozoan sp.18	–0.153	0.032	0.215	0.247	–0.184	0.020	0.111
Bryozoan sp.23	–0.656	0.246	0.164	0.253	–0.334	0.025	0.089
Retiflustia cornea	–0.202	–0.100	0.135	0.052	0.096	0.078	0.001
Scrupocellaria sp.	–0.368	–0.217	0.089	0.226	–0.183	–0.014	0.180
Triphyllozoon sp.	–0.437	0.236	0.005	0.081	–0.094	0.007	–0.013
Echinoderms							
Asteroid (mixed spp.)	0.062	0.035	–0.228	–0.139	–0.150	0.107	–0.124
Asteroid sp.11	–0.074	–0.041	0.309	0.033	0.043	0.020	0.041
Astropecten granulatus	0.842	0.290	–0.128	–0.015	0.178	–0.012	–0.043
Astropecten sp.4	1.310	–0.232	0.636	0.264	0.170	0.152	–0.026
Brissopsis sp.2	1.298	–0.293	0.357	–0.106	0.047	–0.084	–0.047
Brissopsis sp.ss	0.306	0.005	–0.045	–0.032	0.005	0.045	0.020
Crinoid sp.12	–0.256	0.097	0.121	0.074	–0.102	–0.064	0.046
Crinoid sp.15	–1.620	0.858	0.010	0.224	0.074	0.046	0.106
Crinoid sp.16	0.003	0.104	–0.269	0.014	0.027	–0.023	–0.020
Crinoid sp.17	–2.161	1.259	0.166	0.315	–0.159	–0.014	0.193
Crinoid sp.19	–1.179	0.603	0.156	0.043	–0.089	–0.061	0.210
Crinoid sp.21	0.256	0.102	0.326	–0.014	0.049	0.063	0.038
Crinoid sp.22	–0.195	0.174	–0.124	0.116	–0.094	–0.073	–0.020
Crinoid sp.26	–0.448	0.368	–0.113	0.048	–0.128	0.032	–0.101
Crinoid sp.27	–0.790	0.446	–0.375	0.357	–0.200	–0.188	0.031
Crinoid sp.5	–1.781	0.989	–0.460	0.389	–0.259	–0.274	0.232
Crinoidea	–0.092	–0.090	–0.001	–0.090	–0.110	0.071	–0.079
Echinoid sp.3	0.013	–0.058	0.269	–0.005	–0.008	–0.022	–0.016
Echinoid sp.6	–0.070	–0.003	0.050	0.128	–0.008	0.006	–0.072
Euretaster insignis	0.027	–0.173	0.298	–0.011	0.071	–0.066	–0.024
Gorgonocephalid sp.1	–0.360	0.030	0.496	0.049	–0.057	0.003	0.045
Holothuria ocellata	0.638	–0.149	–0.229	0.149	0.036	0.071	0.018
Holothurian sp.3	–0.248	0.204	–0.188	0.030	–0.027	–0.041	0.001
Holothurian sp.38	–0.180	0.196	–0.329	–0.019	–0.104	–0.033	–0.047
Iconaster longimanus	–0.143	0.112	0.633	0.183	0.164	0.206	0.087
Laganum sp.2	0.073	–0.052	–0.441	–0.109	0.089	–0.011	–0.108
Laganum sp.3	1.417	0.131	–0.601	0.269	0.121	0.047	0.010
Laganum sp.8	1.213	–0.194	0.506	0.206	0.109	0.181	0.074
Luidia maculata	–0.048	0.049	0.181	–0.044	0.017	–0.000	0.008
Maretia ovata	1.605	0.307	0.478	0.117	–0.185	–0.103	0.111
Metrodira subulata	0.080	–0.018	0.256	0.163	0.065	0.180	0.009
Ophiuroid sp.1	–0.408	0.027	0.376	0.013	–0.040	0.012	–0.039
Ophiuroid sp.34	–0.876	0.205	0.245	0.413	–0.055	–0.011	0.189
Ophiuroid sp.5	–0.054	0.043	0.216	0.121	0.148	0.064	0.046
Pentaceraster sp.	–0.254	0.023	–0.282	0.131	–0.058	–0.046	0.082
Pentacta anceps	0.424	0.280	–0.221	–0.039	–0.072	0.014	0.097
Prionocidaris sp.2	–0.033	0.101	0.307	0.079	–0.122	0.055	–0.104
Stellaster equestris	0.251	0.202	–0.606	0.132	0.203	0.248	0.040
Ascidians							
Ascidia scaevola	–0.033	0.071	0.112	0.164	0.085	–0.070	0.031
Ascidia sydneiensis	0.645	0.023	–0.493	–0.122	–0.035	0.041	0.124
Ascidia sp.1	0.880	0.085	–0.028	0.078	–0.142	0.101	0.084
Cemidocarpa stolonifera	–0.175	0.038	0.245	–0.034	–0.068	0.014	0.023
Herdmania momus	0.674	–0.293	0.219	0.383	0.097	0.230	0.092
Hypodistoma deerratum	–0.198	–0.173	0.290	0.138	–0.047	–0.001	0.039
Microcosmus exasperatus	–0.015	0.224	–0.637	–0.084	–0.014	–0.054	0.069

Species	mud	carbonate	depth	habitat	year	north vs south	open vs closed
Microcosmus helleri	0.251	–0.274	0.325	0.084	–0.317	0.081	–0.119
Phallusia millari	0.943	0.070	–0.159	–0.087	–0.018	0.184	0.067
Polycarpa chinensis	0.299	–0.124	0.202	0.011	–0.149	–0.031	0.064
Polycarpa papillata	0.025	–0.229	–0.225	0.088	0.055	0.118	0.015
Pseudodistoma sp.	0.589	–0.038	0.414	0.186	0.002	0.058	–0.023
Pyura sacciformis	0.288	0.044	0.235	0.028	0.030	0.003	0.093
Rhopalaea tenuis	–0.016	–0.383	–0.341	0.027	–0.163	–0.033	0.086

Environmental Effects of Prawn Trawling in the Far Northern Section of Great Barrier Reef: 1991-1996

Volume 2: Chapters 4 to 7

Final report to
Great Barrier Reef
Marine Park
Authority and
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and Development
Corporation

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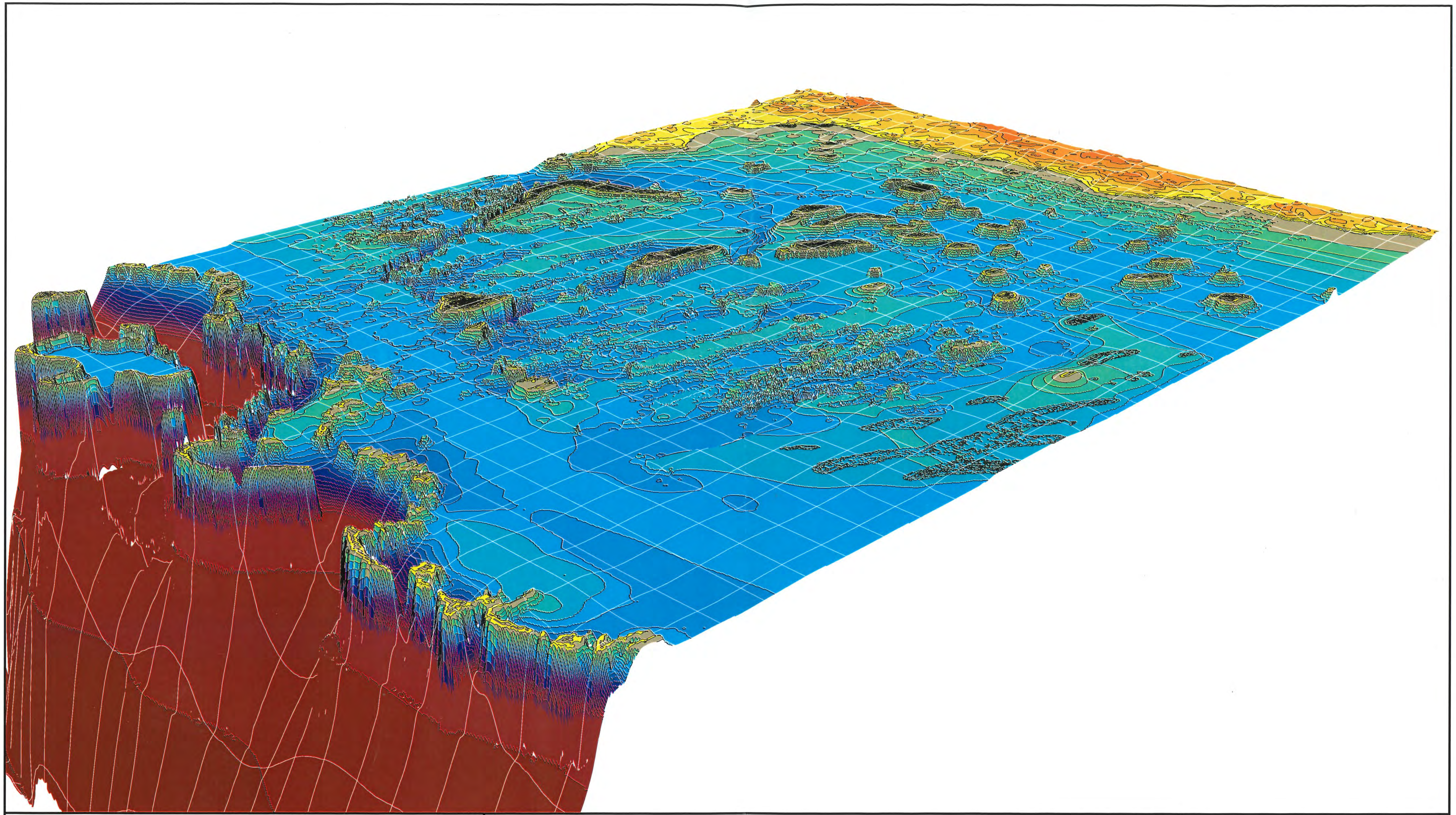
June 1998



Depth / Elevation (Meters)

- 🟧 Higher than 100
- 🟧 75 to 100
- 🟧 50 to 75
- 🟨 25 to 50
- 🟨 10 to 25
- 🟨 0 to 10
- ⬜ -5 to 0
- 🟩 -10 to -5
- 🟩 -15 to -10
- 🟦 -20 to -15
- 🟦 -25 to -20
- 🟦 -30 to -25
- 🟦 -35 to -30
- 🟦 -40 to -35
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- 🟦 -55 to -50
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- 🟦 -65 to -60
- 🟦 -70 to -65
- 🟦 -75 to -70
- 🟪 -80 to -75
- 🟪 -85 to -80
- 🟪 -90 to -85
- 🟪 -95 to -90
- 🟥 -100 to -95
- 🟥 -200 to -100
- 🟫 -500 to -200
- 🟫 -1000 to -500
- 🟫 -2000 to -1000

Schematic of the seabed

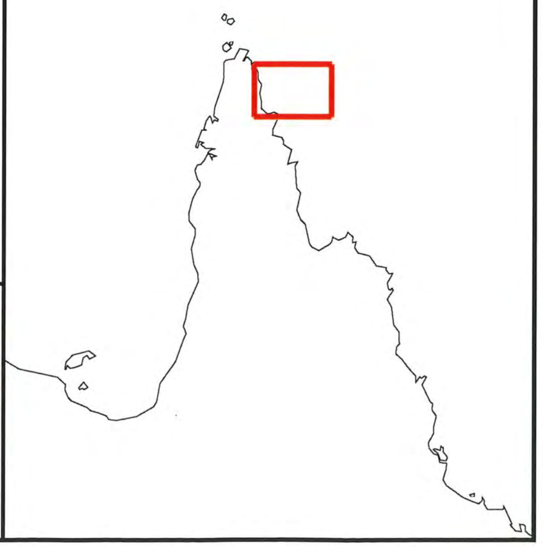
Location of the site is the Far Northern section of the Great Barrier Reef.
The view is from 20°elevation looking from NE to SW.

5000m grid superimposed.

WARNING: Not for Navigational Use

Sources: CSIRO Marine Research

CSIRO
MARINE RESEARCH



ENVIRONMENTAL EFFECTS OF PRAWN TRAWLING IN THE FAR NORTHERN SECTION OF THE GREAT BARRIER REEF: 1991 - 1996

CONTENTS

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CHAPTER 4

BEFORE-AFTER-CONTROL-IMPACT (BACI) EXPERIMENT

Chapter Authors:
R. Pitcher, C. Burridge, T. Wassenberg, and B. Hill

CONTENTS

4 TRAWL IMPACT ASSESSMENT – THE BACI EXPERIMENT

Objective

The objectives of this part of the study were to:

i. Design a Before-After-Control-Impact (BACI) experiment to compare the changes in the benthic communities and associated fish communities of an area that has been experimentally modified by simulated trawling effort with an untrawled area. The power of the experiment was to be defined.

ii. Carry out the BACI experiment designed in the first objective.

These objectives were to be achieved by using information gained in preliminary surveys of the Study Area, which encompassed the Green Zone. Using information gained from the trawl study on the North West Shelf the power of the experiment was set at a 10-fold change in biomass or numbers. The design dictated a large scale replicated experiment that would use a series of plots in an unfished part of the inter-shoal area of the Green Zone. The entire area of half of the plots was to be impacted by a single pass of a trawl and half were to be left as controls. Sampling of the plots was to be by means of a dredge, prawn trawl and fish trawl.

4.1 INTRODUCTION

The study of the effects of trawling on the GBR commenced in 1991 with a major survey of the area closed to fishing (Green Zone) and the adjacent areas open to fishing. The results have been described in Chapter 2. This was followed by a series of manipulation experiments. These were preceded by an analysis of the power of the surveys and experiments to detect specified impact effects and the development of a design for the overall study. Two approaches were developed. Firstly, the fauna within the area closed to fishing was compared to that in the area open to fishing. This approach uses past commercial fishing as an impact (Hilborn and Walters, 1992) and the results have been described in Chapter 3. The second approach was to apply a known amount of effort uniformly with appropriate controls in an experimental protocol called a Before-After-Control-Impact (BACI) experiment. This study was carried out in the Green Zone. This Chapter describes the design, methods and results of this BACI experiment. Another experiment examining the effects of repeated trawling is described in Chapter 5.

The BACI experiment involved a single pulse perturbation to simulate the initial development of trawling in a newly exploited area of the GBR. Typically, the behaviour of fishers in areas that have previously not been trawled is to conduct initial assessments using colour echosounders in order to identify hard ground that might snag the nets. Heavy trawl gear is then towed across the potential trawl ground in order to remove large sponges and patches of coral. In some experiments to test the effect of fishing, the seabed was trawled repeatedly to simulate commercial fishing of the same ground. For example, Gordon et al. (1997) trawled three 13 km long by 200 m wide corridors 12 times with Engel otter trawl each year for three years. In the case of the GBR region, the area of the fishery is very large relative to the fishing effort and so most of the seabed is trawled infrequently. Data from the logbook program operated by the Queensland Fisheries Management Authority (QFMA) and GBRMPA indicates that on average, 70% of 6 x 6 n.mile fishing grids are trawled less than once per year. In order to provide a realistic simulation of this level of fishing effort, in our BACI experiment, the impact was applied by using a single pass of trawl gear. There was consensus amongst researchers and the trawling industry, that a seabed supporting epibenthos such as sponges, soft corals and gorgonians, would be impacted considerably by a heavy trawl. Sainsbury et al (1992) used video to observe interactions between a footrope and sponges on the North West Shelf of Australia. In cases where the outcomes could be confirmed, 90% of sponges were detached. In many cases the fate of the sponges could not be confirmed. If it is assumed that none of these sponges were detached then 43% of all sponges were impacted. However if all of these sponges were detached, then 95% of sponges were impacted.

The objective of the Green Zone BACI experiment was to estimate the effect of a trawl impact on the benthic, fish and prawn communities in an area closed to fishing. Comparisons between the same area before and after it was trawled is a powerful technique rarely available in established trawl fisheries. The BACI experiment in the Green Zone of the Great Barrier Reef was carried out in an area that had been closed to fishing since 1985. During that time there had been some illegal trawling (Sect. 2.6) but it appeared that none of this had taken place in the inter-reefal area chosen for the BACI experiment. Thus the experiment was carried out in an untrawled environment. We expected that a prawn trawl might have different impacts on the various elements of the benthic fauna and so the catch in the trawl would not be an accurate reflection of the fauna. This has already been shown to be the case for fish (Wassenberg et al., 1997). We therefore also used a fish trawl and a large benthic dredge in order to sample a broader range of the species composition of the benthic fauna that could be used as a reference for measuring the impact of the prawn trawl on the various benthic taxa.

Underwood (1994) has discussed the limitation of the conventional BACI approach and ways of increasing the power of BACI experiments. These deal with two problems involving insufficient replication in the general application of the BACI method. Firstly, a single control location does not take in to account possible differences between sites. Thus differences between the impact and control site may be due to an unknown amount of inherent site difference unrelated to the impact. Secondly, systems change with time and especially seasons and so abundances of many populations are 'noisy' making it difficult to identify real differences. In order to overcome these problems, Underwood (1994) recommended increasing the number of control sites and sampling at several time points (nested) before and after impact. In the present study, we addressed the spatial problem by replicating both the impact and the control sites equally. The temporal variability problem was more difficult to deal with because of the remote location of the Green Zone and the consequent considerable cost of visiting the area. It was impractical to conduct before and after sampling on multiple hierarchical time-scales. We included a time factor in the experiment: two sets of full BACI experiments were carried out, one at the end of the dry season and one at the end of the wet season. This would also deal the risk from major short-term events such as a cyclone. Consequently, we would be able to make conclusions about fauna that could reasonably be expected to have relatively stable dynamics over the study period. This would include those with life times of about two years or longer and which did not have major migrations in or out of the study area. Most species of concern were in this category, ie. longer-lived resident fishes, invertebrates and attached fauna. We were also interested in sustained impact effects that would persist for significant periods (more than a few months) rather than transient effects.

4.2 MATERIALS AND METHODS

4.2.1 Experiment Structure

The study area

The study was carried out in the area closed to fishing between 11°15’ and 11°45’S in the far northern section of the Great Barrier Reef (GBR) (Figure 2.01). Because of its zoning classification by the GBR Marine Park Authority, this area is commonly referred to as the Green Zone. The BACI experimental plots were located in the mid-shelf inter-reef/shoal stratum of the Green Zone (Figure 4.01), as any possible expansion of the trawl fishery would be into this stratum. In addition the area had to contain habitat suitable for red-spot prawn, the most likely target species. It also had to include deep off-reef areas (35–50 m), and shallow near-reef areas (20–25 m) with patches of untrawlable seabed. These two areas represent the main types of ground that are trawled in the region and the type of benthos might differ between them. The topography of the seabed in the vicinity of the study sites was extremely complex, as can be seen from the 3D-bathymetry diagram at the front of each volume of this report. Most of the outer half of the Green Zone was uncharted and was surveyed for the first time during the course of this and other associated effects of trawling studies.

Design of the BACI experiment

The design process involved setting the probability of type I (α) and type II (β) errors where the former is the risk of falsely accepting the hypothesis that there is a difference between closed and open areas when there is none and the latter is the risk of falsely accepting the hypothesis that there is NO difference between closed and open areas when a difference exists. Having set α and power ($1-\beta$) at acceptable levels (often 0.05 and 0.80 respectively) it is possible to estimate the sample size required to detect a specified level of impact. Alternatively, given a specified sample size (usually due to resource limits), the level of detectable impact can be estimated. In this section, detectable effect-sizes were estimated for a range of designs, using non-central distribution functions implemented in the SAS statistical software (SAS Institute 1990).

Cohen (1988) introduced the concept of a standardised “effect-size index” (*ESI*). His aim was to define a dimensionless index that specifies an effect-size relative to the variance of a sample. For a test of two means:

(1) $$\underline{ESI} = \delta / \sigma$$ Cohen (1988)

where δ = difference between the means and σ = common population standard deviation. For example, a given effect may be considered large for a homogeneous population with a small variance, whereas the same effect maybe considered small for a heterogeneous population with a large variance. By examining the conclusions for a range of studies, Cohen derived some empirical guidelines for his index: for a “small” effect, the *ESI* was ~0.1; for a “medium” effect, the *ESI* was ~0.25; and for a “large” effect, the *ESI* was ~0.4. As discussed in the introduction, the impacts of trawling were expected to be in the category of “large” effects.

During the descriptive sampling in the first year of this study, more than 1000 taxa were recorded from three different sampling gears (fish trawl, prawn trawl, epibenthic dredge). It was impractical to attempt to include all this information in the design process. The design calculations were based on the results of analysis of variance of taxon weights ($\log_{10}$ transformed) at the taxonomic class level and for the most widespread species (ie. those present in more than half the stations), and were done separately for each of the sampling gears. Because the species level power analysis covered only a small fraction of the data, it was considered that summarising at the taxonomic class level was the most appropriate way to cover the majority of the data for the power analysis. It has been shown that this type of summarisation still retains patterns in data, as many benthic species appear to respond similarly, at the class level, to impact due to their similar life habit (eg. Warwick, 1993).

The objective of this part of the research was to simulate and measure the impact of trawling on benthic, fish and prawn communities of the cross-shelf closure area, in a controlled way. The intention was to compare specifically trawled and untrawled areas. For the experiment to be as relevant and realistic as possible the following concepts influenced the design. (1) The experiment should be established at the largest practical spatial scale. (2) The mid-shelf inter-reefal/shoal stratum was of particular interest to the "Effects of Fishing Issue" because this stratum remains untrawled in many areas of the GBR and has high conservation value. There is incentive for fishermen to trawl these strata because of the occurrence of red-spot prawns — consequently, the potential impact of trawling moving into these areas should be assessed. (3) Experimental plots should be established in red-spot prawn habitat; ie. generally carbonate sand seabed at ~20–50 m depth, because these are the habitats that may attract trawling effort. (4) plots should have epi-benthic structural fauna so that the impact on these can be assessed. (5) Two basic types of grounds existed in which trawling should be simulated; open areas where all ground within the plot can be impacted (complete impact) and areas with "hook-ups" within the plot that are avoided because of potential net damage (incomplete impact). The latter habitats tend to occur in shallower water nearer to coral reefs or shoals and the former tend to occur in deeper open areas further from reefs and shoals — both types of habitat should be represented in controls as well as treatments.

Design principles:

The objective of this research and the specific design principles dictated the following:

- The main effect of interest was the change in the benthic and demersal communities of the treatment plots as a result of experimental impact, relative to control plots that presumably do not (but may) change. Given the limited number of plots that could feasibly be established and the likely high variance between plots initially, the power of the design would be enhanced considerably by sampling each plot before, as well as after, the experimental impact (ie. a "before-after" factor). Consequently, the statistical term of greatest interest would be the interaction between Impact and Time (before-after). This is known as a BACI experiment and their design and analysis has been discussed fully previously (eg. Green 1979, Underwood 1991, 1992, 1993).

- Due to seasonal differences in the biology of organisms and uncontrollable temporal factors of the environment (eg. cyclones, ENSO etc.), it would be desirable to start separate sets of plots at different times — end-of-dry and end-of-wet seasons.

- To achieve greatest power for the amount of sampling effort that will be applied, there should be balanced distribution of stations across Seasons, Habitats, Impact plots, and

Times (before-after). Treatments should be allocated randomly to plots and sampling stations should be distributed randomly within experimental and control plots.

- The design was required to incorporate the possibility of sampling to measure recovery of the seabed habitat following the completion of the experiment. Planned resourcing included one additional post-BACI experiment sampling. Continuation of sampling was subject to review.
- The minimum structure for this design was: 2 × Season by 2 × Depth by 2 × Impact by 2 × Plots by 2 × Time by *n* × Stations. If greater power was required, additional sets of plots should be established to increase the degrees of freedom in the design, rather than increasing the number of stations per plot, even though this may improve the variances of the plot means.

Size of experimental plots:

An initial step in the experimental design process was to decide on the appropriate scale of the experimental plots. These would have to be as large as possible given the scale of commercial trawling operations, movement patterns of fishes, prawns and other non-sessile organisms, research sampling with replication, and the desirability of buffer zones around manipulated plots — yet small enough to permit replicate plots to be established with realistic levels of funding. Plots would have to be at least 1.5 n.mile long because 30 minute research trawls, at 2-3 kn, cover strips of seabed almost 1.5 n.mile long. Square plots (ie. about 1.5 n.mile wide also), within which replicate stations would be sampled, would approach the desired scale objective more closely than narrower designs. However, it was also clear that power would be related to the number of plots in the experiment and, given the cost of establishing plots within a given budget, there was likely to be a trade-off between plot-width and number of plots. Consequently, a range of plot widths (0.16–1.56 n.mile) was examined in the following cost-benefit and power analyses; though it was felt that widths <~0.5 n.mile would be too small given the objectives with respect to scale.

Cost-benefit analysis:

It was estimated that ~0.75 hrs of effort for each of two trawlers would be required to manipulate strips 0.03 n.mile wide in each impact plot. The cost of establishing each impact plot would be dependent on its width (ie. number of 0.03 n.mile strips) and should be amortised across the control plots, before and after sampling as well as the first recovery sampling. There were also costs associated with travelling to each plot estimated at 0.5 hrs for each of two trawlers for each of the three occasions. The cost of sampling each station was estimated at 2.5 hrs to deploy 3 gear types from two trawlers for each of the three occasions.

Given these time costings for establishment of a range of plot sizes, plus the time required for sampling, the most efficient number of stations to sample within each plot was estimated by re-application of the cost benefit analysis of the spatial hierarchical sampling used in the Open vs Closed comparisons — see equation (2), chapter 3, using variances from the descriptive sampling for stations and locations (as an estimate for plot level variances). The cost-benefit analysis was conducted for a range of plot widths (0.16–1.56 n.mile); and for 15 classes of benthic fauna and 17 species of benthos sampled by the benthic dredge; 15 classes of benthos, 8 prawn species and 32 bycatch species sampled by the prawn trawler; and 15 fish families and 38 fish species sampled by the fish trawler.

Minimum detectable differences:

To simplify the power analysis, without affecting its applicability, the full BACI design could be simplified by examining only the differences between the plot means before and after the manipulation. Thus the time factor was eliminated and the design reduces to a relatively simple three factor case and obviates the need to consider the interaction term, Impact*Time. The factor of interest becomes simply Impact. Further, because the design was fully orthogonal and there were only two levels for Impact (control, trawled), and we were primarily interested in negative impacts, the power analysis could be treated as a 1-tailed *t*-test of the level means for the factor Impact. The fact that other factors were in the design was accounted for by the reduced degrees of freedom for Impact in the factorial design compared with a simple two sample case.

Variance estimates for the plots were required as input for *a priori* power calculations for this simplified design. Because of the implied averaging of station data to give plot means, which would be differenced before-after, the variances were re-estimated from the Location variance (s^2_L) and Station variance (s^2_S) partitioned from the descriptive study, as follows:

From partitioning of variance in the descriptive study, we have:

(2) $$\underline{MS}_{L(ZS)} = n.s^2_L + s^2_S, \text{ and } \underline{MS}_e = s^2_S$$

For the design of the BACI, we assumed that $\underline{MS}_{L(ZS)}$ (from eq.8, for any given n) would be representative of the likely mean square for the Plot level, ie. $\underline{MS}_{Plot(SHI)}$. However, in the simplified design considered here, the means of n stations in each plot P were used and the variance of the means depends on the number of stations averaged in each plot, ie. the variance of the mean of any given Plot i before or after impact was:

(3) $$s^2(\overline{P}_i) \approx \underline{MS}_{L(ZS)}/n = (n.s^2_L + s^2_S)/n = s^2_L + s^2_S/n$$

Further, the sample data in the simplified design would be the differences between the means of the same plots before-after impact and the variance of this difference will be additive. However, because the same plot would be sampled before and after, the plot level term (and its associated variance, estimated by s^2_L) cancels out. Whereas, because a different set of random stations would be sampled, the station level contribution to the variance (estimated by s^2_S) was additive. Hence, mean square error of the simplified design was estimated by:

(4) $$\underline{MS}_{e(\text{simplified design})} = s^2(\overline{P}i_{\text{before}}-\overline{P}i_{\text{after}}) = 2.s^2_S/n$$

Given the available resources, it was estimated that the maximum possible amount of field time was about 100 vessel days and the maximum number of samples from all gears that could be sorted was about 100 stations for each sampling time. The minimum difference (δ) between the control and impact plots, that could be detected by design alternatives falling within these resource limits, was given by a re-arrangement of the equation for the non-centrality parameter (γ) for the *t*-distribution (with equal sample size n' for each level of the Impact factor) — see equation (6) in Chapter 3. As with the Open vs Closed comparison, γ was chosen to give power ($1-\beta$) of 0.80 by iterating the SAS function PROBT, but in this case only negative effects were considered (γ is negative), ie. a one-tailed test, so power was evaluated as follows:

$$\text{Power} = \text{PROBT}(T, \nu, \gamma) \tag{5}$$

where T = critical value of the t-distribution for $\alpha = 0.05$, ν = degrees of freedom for plots (calculated from the number of levels of each factor: S×H×I×(P-1)). For a one-tailed test of negative effects, T is negative and was evaluated with the SAS TINV function as follows:

$$T = \text{TINV}(\alpha, \nu) \tag{6}$$

The analysis of minimum detectable differences was conducted for a range of plot widths, numbers of stations within plots, numbers of plots for each combination of the main effects, and for 15 classes and 17 species sampled by the benthic dredge; 8 prawn species, 15 classes and 32 species of bycatch sampled by the prawn trawler; and 15 fish families and 38 fish species sampled by the fish trawler.

Design Outcomes for the BACI experiment

Size of experimental plots and Cost-benefit analysis:

The choice of plot size in the BACI experiment was bounded by a number of conceptual constraints, eg. plots would have to be at least 1.5 n.mile long, as described in the methods. However, within these bounds, plot size was closely inter-twined with the cost-benefit analysis (and power analysis). The results for a range of plot widths (0.16–1.56 n.mile) are shown in (Table 4.01). The time cost (hrs) to impact plots increases linearly with plot width; the cost amortised over the entire experiment was much less, but still increased linearly. The results of cost-benefit analysis, based on amortised plot costs, station costs, and plot and station level variances, showed that the calculated number of stations per plot, averaged for all 145 classes or species, increased non-linearly with plot width (Table 4.01) — and step-wise, because the number of stations must be an integer. The optimal widths were those where cost-benefit was closest to an integer value for number of stations (shaded in Table 4.01); these were the three plot sizes examined in the analysis of minimum detectable differences.

Total costs per plot decreased with narrower plots, as did costs per station also — which is advantageous. On the other hand, the proportion of the plot area free from sampling (and the impact due to sampling) increased with narrower plots (Table 4.01). The trade-off between these two considerations meant that though 0.26 n.mile wide plots were the least costly, the sampling fraction (as a proportion of the area of the plot) was very high and there was a risk that the sampling could affect the results (non-independence); further, such narrow plots were the greatest compromise in terms of the "largest-possible-scale" aims of the study. Hence, narrow plots, with 2 stations, were excluded from contention, although for completeness they were included in the discussion of power below. At the other extreme, the 1.26 n.mile wide plots had the most favourable sampling fraction, but were the most costly and fewer plots of that size could be established. The final choice of plot size was contingent on the power analysis (below).

Table 4.01 Results of cost-benefit analysis in terms of optimum number of stations per plot, for a range of plot widths. Direct costs (hours) required to manipulate and sampling each plot, as well total costs (hours) are shown.

Plot width	Plot Impact cost	Plot sample cost	Amortised Plot cost hrs	Station Cost hrs	cost/ benefit (stns/plot)	Integer stns/plot	Total cost per plot	Total cost per station	% area free from sampling
0.16	8	1	2.33	2.5	1.80	2	22.0	11.0	0
0.26	13	1	3.17	2.5	2.10	2	24.5	12.3	40
0.36	18	1	4.00	2.5	2.36	2	27.0	13.5	60
0.46	23	1	4.83	2.5	2.59	3	37.0	12.3	55
0.56	28	1	5.67	2.5	2.81	3	39.5	13.2	64
0.66	33	1	6.50	2.5	3.01	3	42.0	14.0	70
0.76	38	1	7.33	2.5	3.19	3	44.5	14.8	74
0.86	43	1	8.17	2.5	3.37	3	47.0	15.7	78
0.96	48	1	9.00	2.5	3.54	4	57.0	14.3	73
1.06	53	1	9.83	2.5	3.70	4	59.5	14.9	76
1.16	58	1	10.67	2.5	3.85	4	62.0	15.5	78
1.26	63	1	11.50	2.5	4.01	4	64.5	16.1	80
1.36	68	1	12.33	2.5	4.14	4	67.0	16.8	82
1.46	73	1	13.17	2.5	4.28	4	69.5	17.4	83
1.56	78	1	14.00	2.5	4.41	4	72.0	18.0	84

Minimum detectable differences:

The results of the analysis of minimum detectable differences in relation to costs are summarised in Table 4.02. These were conducted for a range of plot widths (0.26, 0.66, 1.26 n.mile), numbers of stations within plots (2, 3, 4), numbers of plots (2, 3, 4) for each combination of the main effects, and for 145 taxa sampled by three gear types. For the nine designs examined, minimum detectable differences (δ), averaged over all gears and taxa, ranged from the capability to pick-up a reduction in biomass down to <21% for the weakest design, to <45% for the strongest. Thus, all designs met the first criterion for power (ie. δ = 10-fold or less). However, Cohen's *ESI* ranged from 0.68 for the weakest design, to 0.32 for the strongest; for only three of the designs was *ESI* <0.4 corresponding to Cohen's guidelines for a "large" effect (though another two were close, ie. *ESI* <0.45). Time costs for the field component of the experiment ranged from 36 days for the weakest design, to 188 days for the strongest. However, the strongest design, and two others, were beyond the resources of the project. Between the extremes, there was no direct relationship between costs and power; some affordable designs clearly would be more powerful than other designs (Figure 4.02).

Table 4.02 Average detectable effect sizes (δ) for a range of BACI designs with different sizes and numbers of plots, and different numbers of stations within plots. The impact costs and total costs of each desing differs. The average detectable effect is also presented as (back-transformed) impact/control biomass ratio (%). The corresponding Cohen's ESI is shown for each design. Note average variances are presented only as an indication, these were not used in the power analysis.

plot width n.mile	#plots per combi	#stns per plot	impact cost hrs	Total #plots	Total #stns	days	Average s^2 of plot mean	*t* non-centrality γ	average δ	Average detectable effect	Cohen ES Index
0.26	2	2	104	16	32	36	0.379	-2.727	0.78	20.7 %	0.68
0.66	2	3	264	16	48	61	0.252	-2.727	0.637	26.7 %	0.56
1.26	2	4	504	16	64	94	0.189	-2.727	0.551	31.3 %	0.48
0.26	3	2	156	24	48	53	0.379	-2.599	0.607	28.3 %	0.53
0.66	3	3	396	24	72	92	0.252	-2.599	0.495	34.9 %	0.43
1.26	3	4	756	24	96	141	0.189	-2.599	0.429	39.7 %	0.38
0.26	4	2	208	32	64	71	0.379	-2.559	0.518	33.4 %	0.45
0.66	4	3	528	32	96	122	0.252	-2.559	0.423	40.3 %	0.37
1.26	4	4	1008	32	128	188	0.189	-2.559	0.366	45.1 %	0.32

In general, designs with two plots ('2 Plot') designs were less powerful than '3 Plot' designs, and '4 Plot' designs were the most powerful (Figure 4.02). However, '4 Plot' designs were also the most costly, and if the narrow plots with 2 stations alternative is excluded as discussed in the previous section, then none of the '4 Plot' designs were feasible. In the case of '3 Plot' designs, the option with 4 stations in the widest plots was excluded due to costs, leaving only the medium width Plots with 3 stations. The estimate of Cohen's *ESI* for this design was 0.43, which was sufficiently close to Cohen's guide-lines for a "large" effect (*ESI* = 0.4). The average power of the '3 Plots with 3 stations' design was sufficient to detect reductions by ~65% of biomass in impact Plots down to less than ~35% of biomass Before or in Controls — well within the power criterion of a 10-fold reduction in biomass. For different sampling gears, average minimum detectable effects ranged between reductions down to less than ~27% for classes in dredge benthos and reductions down to 47% for classes in prawn bycatch (Table 4.03). For individual taxa, minimum detectable effects ranged between down to ~6% for sponges caught as bycatch in prawn trawls and down to ~87% for the classes polychaetes, gastropods and bryozoans caught as bycatch in prawn trawls. Over all taxa, the 66 percentile range of minimum detectable effects was reductions down to 21%–49% (results for each taxa are shown in Appendix 4.A).

A number of other options were examined for increasing the power, such as progressively increasing the density of stations in the 0.66 n.mile wide plots. However, aside from the issues relating to excessive sampling fraction raised above, if 4 stations were sampled in a '3 Plot' design the combined field time and sorting costs would exceed resources. In the case of '2 Plot' designs, the option with 6 stations in 0.66 n.mile wide plots was the only one having sufficient power (*ESI*=0.39) with costs (94 days) within resource limits. However, the sampling fraction was extreme — none of the area of the plots would free from sampling. Further, the '2 Plots' designs have less degrees of freedom and so would be a less robust analysis.

Table 4.03 Summary of cost-benefit analysis (optimum stations per plot) and estimated detectable effect-sizes ($\delta \log_{10}$ g) for the '3 Plot, 3 Stations' BACI design. Values shown are averages for taxonomic classes and species sampled by the three gear types. The average detectable effect size is also presented as (back-transformed) impact/control biomass ratio (%). Cohens' ES Index = 0.43 in each case.

BACI Experiment	cost benefit	δ	Ratio %
Dredge Class averages	3.709	0.592	27.3%
Dredge species averages	3.165	0.566	28.7%
Prawn bycatch class average	4.205	0.411	46.7%
Prawn bycatch species average	2.398	0.417	39.9%
Fish trawl family average	2.339	0.540	30.3%
Fish trawl species average	3.650	0.527	31.0%
Prawn species average	1.605	0.415	40.3%
OVERALL	3.010	0.495	34.9%

Table 4.04 Full specification of the ANOVA Design of BACI experiment, including within plots error strata. Only the between plots sources were required for the power analysis.

Source	levels		df	Denom.
Between plots:				
Season	2	Fixed	1	P(S,H,I)
Habitat	2	Fixed	1	P(S,H,I)
Impact	2	Fixed	1	P(S,H,I)
S*H	4	Fixed	1	P(S,H,I)
S*I	4	Fixed	1	P(S,H,I)
H*I	4	Fixed	1	P(S,H,I)
S*H*I	8	Fixed	1	P(S,H,I)
Plots(S,H,I)	3	Random	16	e
Within plots:				
Time	2	Fixed	1	T*P(S,H,I)
S*T			1	T*P(S,H,I)
H*T			1	T*P(S,H,I)
I*T			1	T*P(S,H,I)
S*H*T			1	T*P(S,H,I)
S*I*T			1	T*P(S,H,I)
H*I*T			1	T*P(S,H,I)
H*S*I*T			1	T*P(S,H,I)
T*P(S,H,I)			16	e
e	3	Random	96	

Consequently, the design chosen for the BACI experiment was 3 Plots per combination of fixed factors, with 3 stations sampled before and after in each 0.66 n.mile wide Plot. This would give a total of 24 Plots and 72 stations and was estimated to require about 92 days of field-time. The full design of the BACI impact of trawling manipulative experiment is shown in Table 4.04. The 'within Plots' sources of variation are also shown and the full design will be analysed, although this was not necessary for the estimation of power.

The experimental impact

The impact was a one-off series of trawls entirely covering the experimental plots. This would simulate the common practice of prawn trawlers to trawl the majority (about 70%) of trawl grounds only occasionally but sufficiently often to possibly have an impact on the benthos. Twenty four plots were established, each 2.78 km by 1.22 km. The first set of 12 plots (Season 1) was established in November–December 1993. The second set of 12 plots (Season 2) was established in March 1994. Six pairs of plots were in shallow water (~ 20–25 m depth) and six pairs in deep water (~ 35–50 m depth). Six shallow (one of each pair) and six deep plots were chosen at random from each set of plots and treated by trawling all over (total 12) with the remaining 12 being left as controls. The position of the plots is shown in Figure 4.01 and the timeline for the experiment is shown in Figure 4.03. The impact involved trawling over predetermined, contiguous, adjacent, parallel tracks in each of the 12 experimental plots. In total, 44 such trawls were required to cover each impact plot with an intensity of one trawl per unit area. Thus it took 528 trawl tows to cover all 12 impacted plots. Two trawlers were used and they were guided by a differential GPS system with an accuracy of 2–5 m.

Before and after sampling

All 24 plots were sampled immediately before the experimental trawling impact and again six months afterwards using the benthic dredge, prawn and fish trawls. The six month delay was chosen to avoid short term effects such as animals being attracted into an area of disturbance. To ensure that each before and after sample was independent, each plot was divided into six 185 m–wide lanes with a 55 m wide buffer zone on each side of the plot. These lanes were then designated at random as either before or after. This gave three lanes in each category in each plot. Each lane was subdivided into ten strips the width of the area swept by the prawn trawl (about 18.5 m). For the pre-impact sampling, one strip was chosen at random from each of three of these lanes and one sampling device was towed along it. The benthic dredge was towed for about 600 m, the prawn trawl for about 1.85 km and the fish trawl for about 2.8 km. For the six month post-impact sampling, another strip was chosen at random from each of the remaining three of the six lanes and the three sampling gears were towed along separate lanes. This gave three random samples for each sampling method from each of the 12 experimental and 12 control plots. If all samples were collected, there would have been a total of 144 samples for each type of gear. For a variety of reasons (bad weather, rough seabed and gear problems) not all gear was used at every site. All prawn trawl samples were obtained but three control and one impact fish trawl samples were missed as were one control and two impact dredge samples.

4.2.2 Sampling methods and data preparation

Dredge sampling

The Church dredge was 3 m wide, 1 m high steel frame weighing about 200 kg, with a 3 m long net (25 mm stretched mesh) attached to the rear of the frame. The dredge ran on the seabed on skids and the bottom of the net opening was supported by a steel bar which was level with the skids. Unlike some types of dredge, this design sampled the fauna living on the seabed but not the infauna. The dredge caught small numbers of fish but, because of the superior fish sampling ability of the two types of trawl, we have not incorporated these dredge-captured fish into the analysis of the dredge data.

Prawn trawl sampling

The research vessel used was a former prawn trawler, the FRV *Gwendoline May.* She was used to tow two prawn nets from a beam through an A-frame at the stern. These two nets were equivalent to half of the four-net configuration used by commercial trawlers. This modified rig was used because of the danger of hooking up on the uncharted and rough bottom. The nets were Florida Flyers, with an 8 m headrope connected with 0.9 m of 8 mm chain to two standard otter boards (214 cm x 85 cm, steel frame with timber slats) and a steel skid between the two nets. An 8 mm ground chain was suspended from the footrope with about 5 links of chain at each hanging so that the ground chain hung about 200 mm below the footrope. The body of the trawl net consisted of 54 mm stretched mesh with a codend of 50 mm stretched mesh. Each two was about 30 min covering 2.78 km. Swept area was estimated as 28 836 m^2 assuming a 70% spread of each net (Sparre et al 1989).

Fish trawl

A commercial trawler the FV Clipper Bird, was used to tow a Frank and Bryce fish trawl having a 26 m headrope and a 32 m footrope fitted with wire and rubber rollers on 250 mm drop chains. The mesh of the wings was 225 mm stretched mesh, with 150 mm in the body, gradually tapering to a 100 mm extension, and a codend of 50 mm mesh. Two steel otter boards (200 cm x 150 cm) weighing about 600 kg each spread the net. The spread of the net opening was about 65% of the headline length. Each wing of the net was attached to the otter boards by 30 m bridles and about 10 m of connecting links and chain, which gave a spread of about 42 m. The spread at the wing ends was about 18 m. The hauling speed of the net along the seabed was kept at about 3 knots (5 to 7 km/h).

Processing of catches

The catch of the dredge was sorted on deck and all large items such as sponges, coral lumps or rocks, were removed, identified and weighed. The remainder of the sample was either kept in its entirety or, if the catch was large, a subsample of between 25 and 60 kg was retained. The rest of the catch was then weighed and discarded. The subsample was examined further and, if relatively uniform, about 10 kg was retained as a subsample and the rest was weighed and discarded. If the subsample contained a large number of large starfish, holothurians, Pinctada sp, or large volumes of algae, they were removed, identified as far as possible, counted and weighed before discarding. The rest was frozen and taken back to the laboratory where the composition was identified as far as possible, counted and weighed.

The catch of each fish or prawn trawl haul was spilled onto a sorting tray and large animals (fish, rays, sponges or coral lumps) were identified and weighed on board. The remainder of the sample was either kept in its entirety if it weighed less than about 40 kg, or, if it was larger, a subsample of about 20–30 kg was retained. The rest of the catch was weighed and discarded. The samples were frozen and taken back to the laboratory for processing. In the laboratory, frozen samples were defrosted, sorted into species, counted, weighed and up to 50 individuals were measured (standard lengths) for each fish species. The total weight of the species in the sub-samples was adjusted to take into account the subsampling of the original catch.

4.2.3 Statistical analysis

Implementation of BACI model

The benthic dredge data consisted of weights and numbers for each species. These were transformed to the $\log_{10}$ scale to remove the mean-variance relationship and homogenise the variance as far as possible. To handle the problem of zeros, a constant set to half the smallest non-zero value was added to all data. This empirical approach was found to have two advantages over simply adding a constant such as 1. Firstly the residuals followed a more nearly normal distribution and secondly the variance was not forced to a high value simply because of the value 1 being a large distance from the rest of the data on a log scale. This approach was considered to be the most consistent possible taking into account the many species with abundances varying on different scales.

Restricted Maximum Likelihood (REML) was chosen for analysing the data. This method can accommodate the mixture of fixed and random effects; the need to estimate nested components of variance for use in posthoc power analysis; and the fact that perfect balance could not be achieved for all datasets due to sampling problems. The SAS implementation of REML (PROC MIXED) was used. At the plot level, the design was a fully balanced 2^4 factorial with the factors Impact, Season, Depth and sampling Time. The levels of each factor are shown below. There were 12 plots for each level, with three plots for each four-way combination of Impact, Season, Depth and sampling Time.

Impact (I)	Control or Impact
Season (S)	Season of impact timing: end of dry season or end of wet season
Depth (D)	Shallow sites (20–25 m) and Deep sites (35–50 m)
Time (T)	Sampling timing: just Before Impact or six months After Impact.

The following SAS model was fitted:

Response variable = Impact |Season |Depth | Time

Plot (Impact*Season*Depth)

Time*Plot (Impact*Season*Depth)

Station (Time*Plot [Impact*Season*Depth])

The response variable was log-transformed weight or number. Impact, Season, Depth and sampling Time were treated as fixed effects and Plot (Impact *Season *Depth), sampling Time *Plot (Impact *Season *Depth) and Station (Time *Plot [Impact *Season *Depth]) were treated as random effects.

Results of this mixed model analysis are presented in two ways. Firstly, through F-tests of the sums-of-squares for the main effects and interactions corresponding to fixed effects. Secondly, through linear contrasts among specific combinations of means. There are 15 terms in the analysis of variance corresponding to the main effects and interactions of the four fixed effects in the analysis of variance. Those terms of most interest relate to the impact. The interaction of main interest was the Impact-by-Time two-way (IT) but there were several higher-order interactions: Impact-by-Season-by-Time (IST); Impact-by-Depth-by-Time (IDT); and Impact-by-Season-by-Depth-by-Time (ISDT).

Many fish species were rarely caught, so we restricted analysis to those found in at least 10% of the stations in control plots (69 stations for fish trawl, 72 for prawn trawl). Because of the small number of fish caught in the dredge and the apparent inefficiency of this device for catching fish, we did not include an analysis of dredge-captured fish. This amounted to 57 species in the fish trawl (85% of the fish biomass) and 89 species in the prawn trawl (95% of the fish biomass). The resulting data sets were then analysed at the species level in the same way as for the dredge data groups.

Efficiency of the prawn trawl

We compared the catch rate of benthic plants and invertebrates caught by the prawn trawl with catch rates of the dredge as a complementary indication of the impact. Because of the design and weight of the dredge and the way it scraped the seabed, we assume that it caught nearly 100% of the sessile or slow moving organisms in its path on trawlable ground. We calculated the efficiency of the prawn trawl for each taxonomic group by expressing the density estimated from the swept area prawn trawl catch as a percentage of the density estimated from the swept area dredge catch.

4.3 RESULTS

4.3.1 Seabed benthos and fish

The seabed in the region where the experiment was carried out consists of large stretches of soft sediment with occasional patches of epibenthic communities of sponges, gorgonians and corals. Figure 2.15 a–h in Chapter 2 shows the types of seabed communities found while Figure 2.16 a–b shows the distribution of the various types along two transects. The epibenthos has an associated fauna of fish and invertebrates. These patches of epibenthos represent islands of high diversity surrounded by areas devoid of much structure. The epibenthos patches were often encountered on slightly raised seabed, and video transects indicated they made up around 5% of the seabed. During the experimental trawling impact on the plots, 37.7 t of biological benthic material was removed by the trawlers (Figure 4.04). About five times more material (32 t) was removed from the shallow plots compared to the deeper plots (6 t). Despite the large total amount removed, the density of benthos removed by the prawn trawls was only 15.7 kg ha^{-1} in the shallow and 2.8 kg ha^{-1} in the deep. The distribution of taxonomic groups varied with depth, some being significantly more abundant in deep and others more abundant in shallow water (Table 4.05). Although some of these differences were very large – for example in the case of the bivalves, others were relatively minor. Although significantly more gorgonians were removed from shallow than deep plots, the difference is slight and may not be meaningful.

Most classes of benthos, except for the cephalopods and marine plants, were found in at least 70% of the 141 dredge hauls. The dominant group in the benthic dredge samples was bivalves (mostly the small oyster *Pinctada* sp) which accounted for about half of the catch. Algae and sponges were the next most abundant. The remaining classes each accounted for only a few percent. The organisms fall roughly into two groups. Firstly sessile forms (eg algae, ascidians, bryozoans, hydrozoans, octocorals, sponges or zoantharians) and secondly mobile animals.

The study area has a rich fish fauna. We identified 190 species of fish in 105 fish trawls taken as controls or pre-impact surveys from treated plots. The prawn trawl yielded slightly more species – 218 species from 108 trawls. Despite this diversity, a feature of the fish fauna is the dominance by a few species. *Lethrinus genivittatus*, for example, was the most abundant species overall, it made up 23% of the fish biomass in fish trawls and 22% in prawn trawls. Ninety five percent of the biomass of prawn trawls was made up by only 89 species. In the case of fish trawls it was even fewer – only 57 species. The subset of species found in at least 10% of stations for fish and prawn trawls is shown in Appendix 4.A.

Table 4.05 The mean weight per dredge haul on control plots in deep (n = 36) and shallow (n = 35) water. The significance level for the BACI depth effect is given. The first five taxa were significantly more abundant in shallow plots; the following group of seven taxa were equally abundant at both depths; the final four taxa were significantly more abundant in deep plots. n = 71 samples for each group.

Group	Wt (kg/haul)		*p*
	Shallow plots	Deep plots	
Zoantharia	7.1	2.4	0.002
Gorgonacea	0.9	0.7	0.001
Asteroidea	4.4	1.0	0.026
Holothuroidea	2.3	0.4	< 0.0005
Bivalvia	39.5	0.1	< 0.0005
Algae	13.6	9.7	0.06
Porifera	7.7	8.8	0.07
Crustacea	0.7	0.7	0.6
Ophiuroidea	0.3	0.4	0.9
Echinoidea	0.3	0.2	0.5
Alcyonacea	0.5	2.0	< 0.0005
Hydrozoa	0.3	1.0	0.008
Bryozoa	0.2	3.5	< 0.0005
Ascidiacea	1.1	6.3	0.007

4.3.2 Analysis of variance

Interactions including Impact and sampling Time

Table 4.06 shows all benthic invertebrate classes or fish species for which there was a significant impact by time interaction – in the form of a two way interaction (IT), three way (IDT, IST) or four way (ISDT). The benthic dredge samples showed no significant two way effects. The IDT interaction was significant for gorgonians, and there was a significant four way impact effect for the cephalopods and crinoids. Asteroids showed a four way effect in the prawn trawl samples. Thirteen species of fish collected in prawn trawls showed significant impact effects, nearly every species having at least one significant three or four way effect. Three prawn trawl species (*Apogon brevicaudatus, Paracentropogon longispinus* and *Paramonacanthus choirocephalus*) had a significant IT effect but no significant three or four way effects. Only six species of fish caught in the fish trawl showed significant effects. One of these species (*Pentapodus paradiseus*) had a significant IT effect but no significant three or four way effects. *Pterocaesio digramma* was significant in both prawn and fish trawl.

Table 4.06 Probability values (where $p \leq 0.05$) in the analysis of variance of weights (Wt) and numbers (No) for species/taxa for which there was significant change. Data based on dredge, prawn trawl or fish trawl samples. I = Impact, T = sampling Time, D = Depth, S = Season. Based on 141 dredge, 144 prawn trawl or 140 fish trawl samples.

	Wt, No	IT	IDT	IST	ISDT
Dredge					
Gorgonacea	Wt		0.036		
Cephalopodea	Wt/No				0.035 / 0.022
Crinoidea	Wt				0.027
Prawn trawl					
Invertebrates					
Asteroidea	Wt				0.045
Fish species					
Apogon brevicaudatus	Wt	0.032			
Apogon semilineatus	Wt/No				0.047 / 0.031
Arothron hispidus	No				0.026
Choerodon vitta	Wt/No				0.035 / 0.035
Dacyloptena orientalis	Wt/No		0.026 / 0.042	0.032/0.020	0.026 / 0.042
Dasyatis leylandi	Wt/No		0.027 / 0.023		0.046
Inimicus caledonicus	Wt/No		0.018 / 0.038		
Lactoria cornuta	Wt		0.036		
Paracentropogon longispinus	Wt/No	0.031 / 0.021			
Paramonacanthus choirocephalus	Wt	0.033			
Pterocaesio digramma	Wt/No	– / 0.010	0.035 / <0.001		– / 0.001
Selaroides leptolepis	No			0.029	
Siganus fuscescens	Wt/No		0.026 / 0.009		
Fish trawl					
Parachaetodon ocellatus	Wt/No				0.044 / .045
Parupeneus heptacanthus	Wt			0.024	
Pentapodus paradiseus	Wt/No	0.026 / 0.018			
Pterocaesio digramma	No		0.049		
Rhynchostracion nasus	Wt/No				0.018 / 0.038
Trachinocephalus myops	No				0.037

4.3.3 Estimated impact effects

The components of the significant three and four-way impacts for the invertebrate groups are given in Table 4.07. The components of the impact for the weight of crinoids in the benthic dredge form a confusing pattern: negative in Season 1 deep and Season 2 shallow plots after 6 months, positive otherwise. The largest and most significant component is the negative impact for Season 2 shallow plots, for which the estimate is twice as large as the standard error.

Table 4.07 Impact details for fauna that had a significant higher-order interaction involving Impact and sampling Time. Significance level is indicated for components of the interaction that are statistically significant ($p \leq 0.05$)

Fauna	Percent occurrence overall	Total weight in control plots (kg)	Device	Highest order interaction	Response variable	Components of impact interaction	Impact estimate	SE	*p*	% change
Gorgonacea	64	54.9	Benthic dredge	IDT	Weight	Deep	-0.60	0.41		-75
						Shallow	0.74	0.42		450
Cephalopodea	29	7.7	Benthic dredge	ISDT	Weight	P1, deep	-0.39	0.48		-59
						P1, shallow	0.97	0.48		833
						P2, deep	0.71	0.48		413
						P2, shallow	-0.15	0.49		-29
					Number	P1, deep	-0.31	0.39		-51
						P1, shallow	0.81	0.38	0.049	546
						P2, deep	0.68	0.38		379
						P2, shallow	-0.16	0.39		-31
Crinoidea	94	156	Benthic dredge	ISDT	Weight	P1, deep	-0.49	0.35		-68
						P1, shallow	0.34	0.35		119
						P2, deep	0.16	0.35		45
						P2, shallow	-0.73	0.36		-81
					Number	P1, deep	-0.41	0.32		-61
						P1, shallow	0.40	0.32		151
						P2, deep	-0.18	0.32		-34
						P2, shallow	-0.49	0.33		-68
Asteroidea	51	15.8	Prawn trawl	ISDT	Weight	P1, deep	0.43	0.54		169
						P1, shallow	0.84	0.54		592
						P2, deep	0.74	0.54		450
						P2, shallow	-1.18	0.54	0.042	-93

The impact pattern for cephalopods in the benthic dredge is also inconsistent: in the shallow plots in Season 1 as after six months they apparently increased markedly (0.97 or nearly a 10–fold increase). This result is probably not reliable, however, because so few cephalopods were caught (11 kg in total from 141 stations). In addition, cephalopods are a highly mobile group that may migrate between habitats and so dredge samples are inadequate for determining their quantitative distribution.

The estimated percentage change of benthos sampled by the dredge and prawn trawl is given in Table 4.08. None of the effects was statistically significant. The results show decreases for some groups (marine plants, echinoids, crinoids and ophiuroids) and increases for others (sponges, cephalopods, holothuroids and asteroids). Several groups showed inconsistencies between the two types of gear (algae, hydrozoans, zoantharians, bivalves, bryozoans, crustaceans and ascidians). We consider that a large part of this inconsistency is due to the poor sampling ability of prawn trawls for many types of benthic fauna as explained below.

Table 4.08 Estimates of the overall impact, standard error of the estimate (SE) and the estimated percentage change in biomass of the various benthic groups. The table is based on data from 141 benthic dredge hauls and 144 prawn trawls.

Group	**Dredge Hauls**				**Prawn Trawls**			
	Percent occurrence	**Estimate**	**SE**	**Estimated % Change**	**Percent occurrence**	**Estimate**	**SE**	**Estimated % Change**
Algae	99	-0.01	0.22	-2	96	0.24	0.17	74
Porifera	92	0.07	0.31	17	83	0.40	0.37	151
Hydrozoa	75	-0.06	0.21	-13	67	0.11	0.11	29
Pennatulacea	13	0.08	0.1	20	14	-0.02	0.07	-5
Gorgoniacea	65	0.07	0.29	17	90	0.42	0.28	163
Alcyonacea	74	-0.10	0.36	-21	81	0.30	0.37	100
Zoantharia	97	0.16	0.22	45	66	-0.06	0.27	-13
Bivalvia	98	-0.23	0.16	-41	100	0.07	0.1	17
Bryozoa	83	-0.35	0.21	-55	56	0.05	0.16	12
Crustacea	84	-0.27	0.33	-46	76	0.41	0.23	157
Gastropodea	29	0.28	0.24	91	91	0.14	0.25	38
Cephalopodea	85	-0.03	0.21	-7	60	0.27	0.15	86
Echinoidea	94	-0.18	0.18	-34	86	-0.08	0.21	-17
Crinoidea	92	0.15	0.31	41	51	0.20	0.27	58
Holothuroidea	74	-0.12	0.3	-24	33	0.03	0.19	7
Ophiuroidea	74	0.32	0.33	109	63	0.30	0.28	100
Asteroidea	96	-0.09	0.16	-19	83	-0.15	0.25	-29
Ascidiacea	84	-0.02	0.25	-5	64	-0.09	0.31	-19

The impacts for fish species are divided almost equally between positive and negative, and the magnitude of the impact is similar in both directions (Appendix 4.B). Eighteen species of fish showed an impact but only four of these showed an overall effect indicating a response on both shallow and deep plots. Two of these, *Apogon brevicaudatus* and *Pentapodus paradiseus*, showed strong positive overall effects indicating a significant increase whereas the other two (*Paracentropogon longispinis Paramonacanthus choirocephalus*) showed decreases. Five species showed a significant difference in impact between shallow and deep plots, where the impact was significant in shallow and not significant in deep. In four of these cases (*Dasyatis leylandi, Inimicus caledonicus*, *Pterocaesio digramma* and *Siganus fuscescens*) the impact was a decrease. *P. digramma* showed a decrease in shallow plots from both prawn trawl and fish trawl. One other species (*Dactyloptena orientalis*) showed a significant increase in deep plots for Phase 1 of the experiment, but not other impacts were significant. The strong increases shown by *A. brevicaudatus and P. paradiseus* may indicate a movement into disturbed areas.

Even though few significant effects were detected, the BACI experiment as at least as powerful as designed. The a posteriori power showed that for some classes the experiment was more powerful than designed whereas for others it was less. Most were very similar. In all cases the experiment was capable of detecting <10-fold changes (Table 4.09) and in most cases a change of less than five fold was detectable.

Table 4.09 BACI experiment: a priori and a posteriori estimates of detectable impact for benthos classes in dredge and prawn trawl, shown as the estimated percentage by which the original population had to be decreased for a change to be detected. Power was set at 80%, α=0.05, SE = Standard Error.

	***A priori* detectable decrease %**		**Actual SE for impact estimate**		***A posteriori* detectable decrease %**	
Species group	Dredge	Prawn	Dredge	Prawn	Dredge	Prawn
Algae		-34%	0.22	0.17	-73%	-64%
Hydrozoa	-84%	-70%	0.21	0.11	-72%	-48%
Pennatulacea			0.10	0.07	-45%	-34%
Octocorallia	-75%	-78%				
Gorgoniacea			0.29	0.28	-83%	-81%
Alcyonacea			0.36	0.37	-89%	-89%
Zoantharia	-69%	-43%	0.22	0.27	-73%	-80%
Bivalvia	-62%	-48%	0.16	0.10	-62%	-45%
Bryozoans	-86%	-13%	0.21	0.16	-72%	-62%
Decapoda	-60%	-31%	0.33	0.23	-86%	-75%
Gastropoda	-65%	-12%	0.24	0.25	-76%	-78%
Cephalopoda	-50%	-63%	0.21	0.15	-72%	-59%
Echinoidea	-85%	-66%	0.18	0.21	-66%	-72%
Crinoidea	-79%	-70%	0.31	0.27	-84%	-80%
Holothurioidea	-89%	-77%	0.30	0.19	-84%	-68%
Ophiuroidea	-81%	-53%	0.33	0.28	-86%	-81%
Asteroidea	-71%	-80%	0.16	0.25	-62%	-78%
Ascidiacea	-73%	-58%	0.25	0.31	-78%	-84%

4.3.4 Efficiency of the prawn trawl

The efficiency of the prawn trawl was expressed relative to the catch of the dredge, which was more likely to sample closer to the true abundance of fauna on the seabed. However, it must be borne in mind that the dredge also probably has biases in catching efficiency of various groups. Prawn trawls captured crustaceans with a higher efficiency than for any other group (Table 4.10). Efficiency was greater than 20% for only two other groups – cephalopods and alcyonarians (soft corals). The efficiency for most groups was less than 10%. Overall it appears that a prawn trawl was not a good sampling device for most benthic organisms. In addition, the different efficiencies for the various groups means that the catch of a prawn trawl is not a good indication of the composition of the benthos.

Table 4.10 The percentage frequency of occurrence, mean weight and estimated density of various taxa captured in 71 dredge hauls and as bycatch in 72 prawn trawls on control plots. The efficiency of the prawn trawl is estimated by expressing the density in the prawn trawl catch as a percentage of the density in the dredge catch.

	Benthic dredge			Prawn trawl			Percent efficiency of prawn trawl relative to dredge
Class	Percent occurrence	Mean weight (kg)	Density (kg/ha)	Percent occurrence	Mean weight (kg)	Density (kg/ha)	
Algae	100	11.61	64.5	96	0.12	0.1	0.2
Porifera	89	8.25	45.8	90	2.45	2.5	5.6
Hydrozoa	85	0.64	3.6	67	0.01	0.0	0.4
Pennatulacea	13	0.01	0.1	19	0.00	0.0	7.1
Gorgonacea	69	0.77	4.3	90	0.13	0.1	3.1
Alcyonacea	77	1.24	6.9	83	1.34	1.4	20.2
Zoantharia	97	4.71	26.2	75	0.85	0.9	3.4
Crustacea	97	0.67	3.7	100	1.36	1.4	38.2
Gastropoda	73	0.24	1.3	58	0.08	0.1	6.6
Bivalvia	76	19.53	108.5	76	0.76	0.8	0.7
Cephalopoda	27	0.11	0.6	92	0.20	0.2	34.6
Bryozoa	87	1.88	10.4	61	0.06	0.1	0.6
Crinoidea	92	2.20	12.2	86	0.13	0.1	1.1
Asteroidea	90	2.71	15.1	51	0.22	0.2	1.5
Echinoidea	62	0.23	1.3	42	0.06	0.1	4.6
Holothuroidea	61	1.31	7.3	64	0.57	0.6	8.1
Ophiuroidea	97	0.35	1.9	88	0.17	0.2	9
Ascidiacea	86	3.73	20.7	74	0.14	0.1	0.7

4.4 DISCUSSION

This study has shown that the impact of a single pass of a prawn trawl in a complex inter-reef area was considerably less than was commonly thought and previously reported (see below). The opinion at the time when the GBR experiment was formulated, was that a single trawl in a previously unfished inter-reef area supporting epibenthos such as sponges, soft corals and gorgonians would have a major impact. In establishing the power of the BACI experiment to detect a trawl impact, we were guided by the impact levels found in other studies and the need to demonstrate a meaningful change. Fairweather (1993) has pointed out that merely detecting some difference in an ecosystem is not enough to indicate an impact or even a meaningful change. Connell (1997) suggested, on the basis of an extensive review, that a decline of less than 33% in coral cover is not ecologically significant. We were aware of only two previous studies that had estimated the degree of impact of single trawls. Van Dolah et al (1987) found statistically significant changes in the number of undamaged sponges (about 33% decrease) and octocorals (about 20% decrease) immediately after the single pass of a beam trawl through an area of high density of these animals. Sainsbury et al (1992) used a video camera mounted on a trawl net to assess the degree of damage to sponges. Because many sponges passed under the net, they were unsure of the fate of half of the sponges passing under the trawl. Where the fate of the impact was known (188 cases), only 10% of sponges remained attached, the remaining 90% were detached from the seabed or caught. If it was assumed that all of the sponges with unknown fate survived, then 43% of the sponges would have been impacted. If all the unknown sponges died, the impact would have been 95%. These data suggested that a single pass of a prawn trawl through an area supporting epibenthos should cause a significant impact. By contrast our experiment suggests an overall impact of around 10%. The reason for the large difference may have been because both Van Dolah et al. (1987) and Sainsbury et al. (1992) measured the impact on that component of the epibenthic community that is most vulnerable to trawling, namely tall sponges and soft corals. We measured the entire epibenthic community, in the case of sponges we did not restrict analyses to the larger species but included the more numerous encrusting species. Many of these animals may sustain little or no damage since they pass below the net. These findings are generally in line with Collie et al. (1996) statement that the major impact of bottom fishing devices is on habitats having a three dimensional structure. The impact is far less on the lower height but usually more abundant component of the epifauna.

The amounts of material collected by a single pass of the trawl in the BACI experiment were quite considerable, around 32 t from the shallow plots and 6 t from the deep plots. These figures underestimate the extent of the impact since, as Sainsbury et al. (1992) pointed out, the amount of benthos recovered in a trawl net is only a small component of the benthos that is damaged by the trawl ground gear. Comparison of the catch of the dredge with that of the prawn trawl in the present study demonstrates that prawn trawls are not efficient sampling devices for benthos. The type of dredge used probably caught most of the sessile and slow moving epibenthos in its path and a comparison of the catch of the dredge with the prawn trawl, gives an indication of the efficiency of the prawn trawl. The efficiency of trawls is high for cephalopods, crustaceans, and soft corals but very low for most sessile organisms. It was also low for slow-moving benthic invertebrates such as the echinoderms and molluscs. The prawn trawl captured only around 6% of the sponges, 3% of zoantharians and less than 10% of the echinoderms, bivalves and gastropods. A single pass of a prawn trawl appeared to impact only a minor proportion of the seabed fauna. This amount was below the level of detection of the BACI experiment even though the power of the experiment was as expected for most groups. The actual impact amounted to an average removal of 13 kg ha^{-1} from the shallow plots and 2.5 kg ha^{-1} from the deep plots. Although these figures appear low, it is important to bear in mind that the inter-reef area in the Green Zone was mostly bare sediment with occasional patches of epibenthos.

The differential catchability of various groups in the prawn trawl suggests that the catch of a prawn trawl gives a misleading impression of the nature of the benthos. Bivalves for example contributed 47% of the biomass in the dredge yet only 12% in the prawn trawl and so were greatly under represented. Sponges were the dominant class (20% of the biomass) in the prawn trawl, yet a relatively small component (11%) in the dredge. Nearly two thirds (64%) of the prawn trawl catch of invertebrates consisted of sponges, crustaceans, zoantharians and soft corals but these four classes accounted for only 22% of the dredge catch. Prawn trawls are also selective with respect to the fish they catch. In Chapter 2, we compared the catch of fish in prawn trawls with that in fish trawls and showed that many species of fish, especially the pelagic species were not captured by the prawn trawl. Ninety-five of a total of 340 species of fish were captured only by the fish trawl and 102 only by the prawn trawl. These data indicate that prawn trawls are selective collecting devices and therefore they have a selective impact.

The extent of the Impact is a central feature of the BACI approach. The Green Zone BACI experiment was designed to detect a 'large' effect (*sensu* Cohen's ESI=0.4) and would have been able to detect decreases of the order of –5× if they existed. We must accept the result that though an impact was applied that removed 38 t of benthos, the effect of a single coverage by prawn trawl gear could not be observed and the actual effect size must have been less than –5×. In the BACI experiment, for an effect size of –5×, the risk of falsely attributing a trawl impact was 5% and the risk of falsely accepting no impact was 20%. For a lesser effect size, the risk of falsely accepting no impact was much greater. The conclusion is that the effect of a single prawn trawl coverage does not appear to have a large impact on the seabed biota. The catch of the prawn trawl relative to the benthic dredge suggested that the impact of a single trawl may have been of the order of 5–10% removal.

Several other studies have detected larger impacts in statistical analysis of experiments. For example, Thrush et al. (1995) were able to detect significant effects in the order of –50% to -60%, for 3 of 14 taxa, three months after a single pass of a commercial scallop dredge. Their 2.4 m wide steel scallop dredge was fitted with a tooth-bar with teeth 10 cm long and could be expected to have a far greater impact than a typical prawn trawl rigged with a foot rope above the seabed attached to a ground chain. It is also easier to detect an impact if the sampled fauna are numerous and vulnerable to the effects of fishing gear. For example, Van Dolah et al. (1987) could detect a decline in the number of intact large sponges in a high density area of sponges but not in a low density area. The scale of these two examples was relatively small (~1,000s of m^2). Sainsbury et al's (1992) video observations showing a 90% impact from a single pass of a trawl, also considered only a highly vulnerable component of the fauna (ie. large sponges). So the level of impact of a single pass of a trawl depends on the type of gear and/or the type of fauna and may, or may not, be statistically detectable in reasonably powerful designs.

Even in cases where the impact of a single trawl was not significant, it is likely that impacts could compound with repeated trawling and become large enough to be detectable. In prawn trawl fisheries, repeated trawling may cause acute and chronic impacts. A high yielding track may be repeatedly trawled many times in one night and may even be trawled repeatedly for many nights in succession (CSIRO unpubl.) — this may cause short term acute impacts. Such a track may or may not be trawled in subsequent years. Even tracks that are not subject to acute impacts may be trawled occasionally over many years — this may cause long term chronic impacts. Acute impacts are assessed in chapter 5 and chronic impacts are considered in chapter 7.

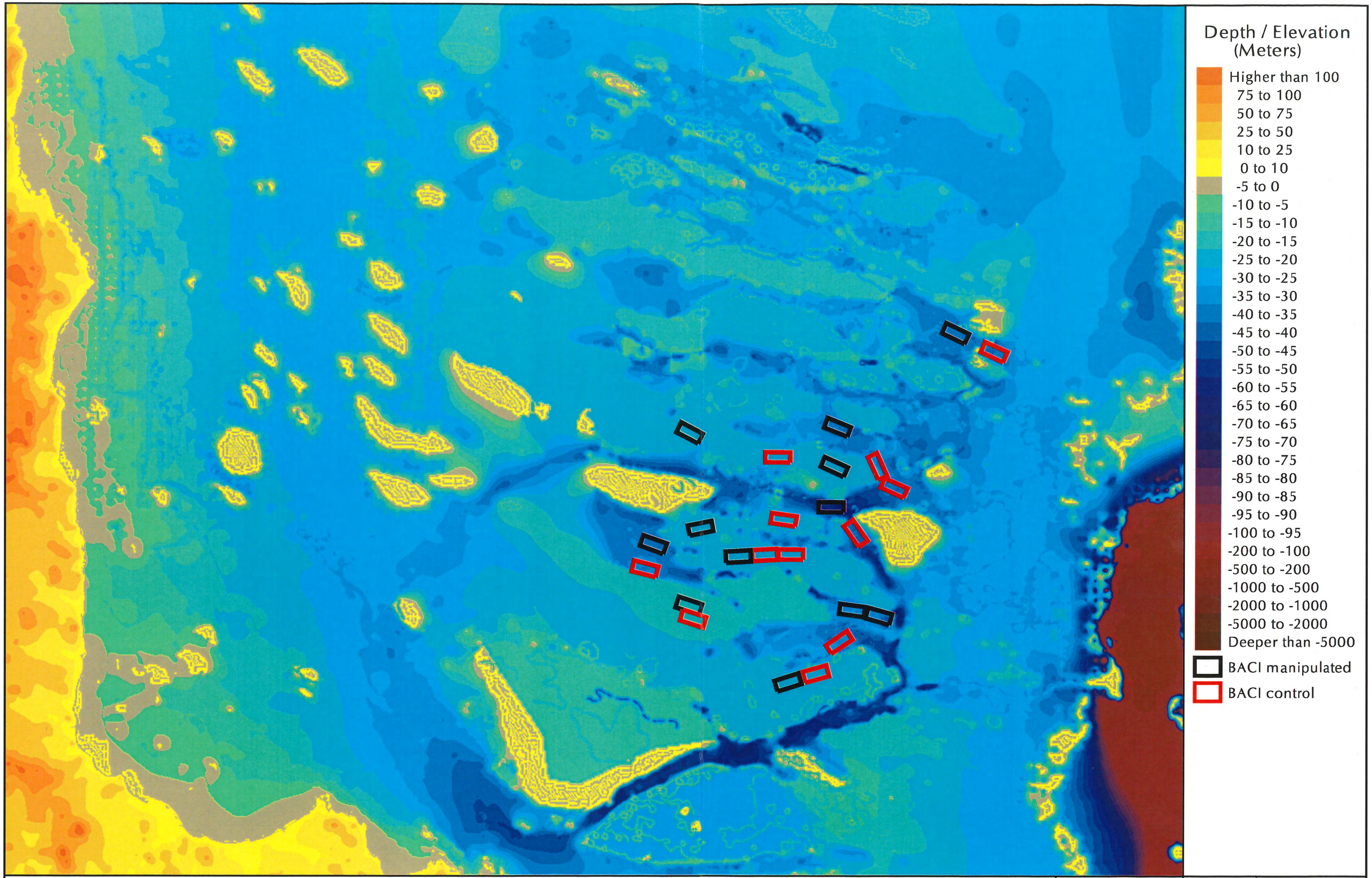
The time delay between impact and subsequent monitoring is important. It is well known that immediately after a trawl or dredge impact some animals move into the disturbed area while others may move out (Ramsay et al ., 1998). In addition, some damaged organisms may remain alive in the short term but will subsequently die. We monitored the experimental plots six months after the impact to avoid these transient effects since we were interested in changes that would be maintained for at least a period of time that was meaningful in terms of management. If fauna not removed by our impact subsequently suffered significant high mortality, we would have been able to detect it in the BACI analysis. Alternatively, it is possible that the extent of recovery may have obscured any impact signal. Van Dolah et al. (1987) found that twelve months after a single trawl experimental impact, the abundance of benthic fauna had increased to pre-trawl densities or greater and damage to sponges and corals could no longer be detected due to healing and growth.

The relatively low efficiency of prawn trawls with respect to the majority of the epibenthos raises the question of whether low levels of trawling represent a threat to the inter-reef communities. Coral reefs are not stable communities living in benign environments but ecosystems subject to frequent physical disturbances on time-scales that vary from minutes to years (Brown 1997). They are subject to natural impacts ranging from major events such as cyclones to minor chronic pressures such as predation (Grottoli-Everett and Wellington (1997). Huston (1979) developed a general model in which species diversity is a function of disturbance and productivity. This has been applied to coral reefs as the Intermediate Disturbance

Hypothesis. This predicts that coral reef species diversity within habitats will be maximal at intermediate levels of disturbance because competitive exclusion will be balanced by destruction of the competitive dominants (Aronson and Precht 1995). Coral reef faunas exhibit considerable ability to recover from damage. This has been well documented in the case of recovery from storm damage. Sponges that remain attached are generally capable of regeneration even if extensively damaged (Fenner, 1991). Wulff (1995) found that the incidence of very small sponges increased by an order of magnitude following a major cyclone suggesting that the massive disturbance had triggered a reproductive response. Corals also have considerable regeneration capacity. Even large fragments and detached colonies can regrow although survival is strongly size-dependent (Highsmith et al. 1980). This ability does come at a cost as regeneration requires diversion of energy from growth and reproduction while injuries provide sites for the entry of pathogens (Hall, 1997).

It is likely that low levels of trawling do not constitute a serious threat to many benthic fauna. They can probably cope with small scale removal and damage. However, continued trawling over the same area represents a chronic disturbance and is probably destructive especially if it exceeds the ability to recover (see Chapter 7). Collie et al (1997) also point out that although the effect of one passage of a fishing net is relatively minor, the cumulative effect and the intensity of trawling and dredging may generate long-term changes in benthic communities. This could include the replacement of the most vulnerable forms by opportunists. There is also overwhelming evidence that repeated fishing of the seabed with dredges and trawls has major impacts (see review by Dayton et al, 1995). Thus although a single pass of a prawn trawl, as may occur where trawling is sparse or infrequent, appears to have little effect there is a strong likelihood that repeated prawn trawls over the same ground will have a progressively more serious impact on inter-reef seabed faunas (Chapter 5).

Figure 4.01 Map of the mid-shelf area of the Cross-Shelf Closure, showing the location of the 12 experimental plots (black) and 12 control plots (red). Shallow plots were located on sandy banks and deep plots were located off the banks. Coral reefs in the area are also shown.



Scale 1:400000

WARNING: Not for Navigational Use

Sources: CSIRO Marine Research

Bathymetric Range Map
Figure 4.01

Showing the location of the BACI sites in the Far Northern section of the Great Barrier Reef.

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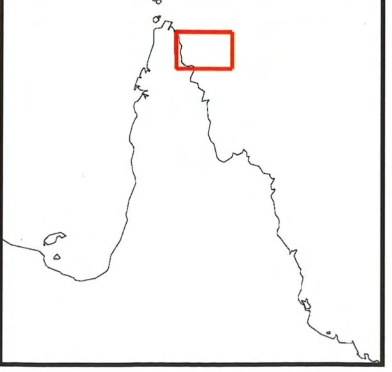

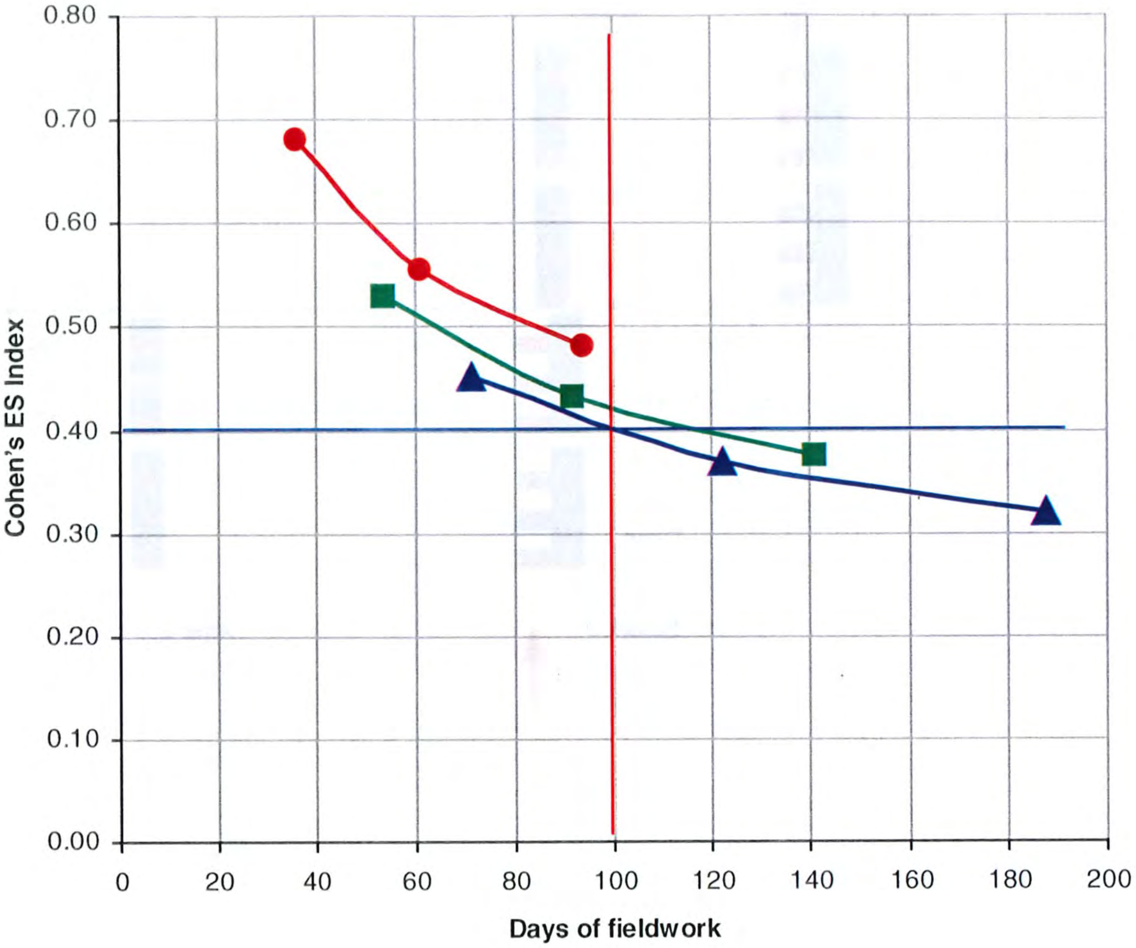

Figure 4.02 Time cost vs relative power (effect size index) for a range of 9 BACI designs: —●— = 2 plot designs, —■— = 3 plot designs, —▲— 4 plot designs. The number of stations per plot increases from 2, 3, 4 from left to right in each case. Cohen's guideline for a "large" effect is shown at ESI=0.4 and the resource limit is shown at 100 days of fieldtime.

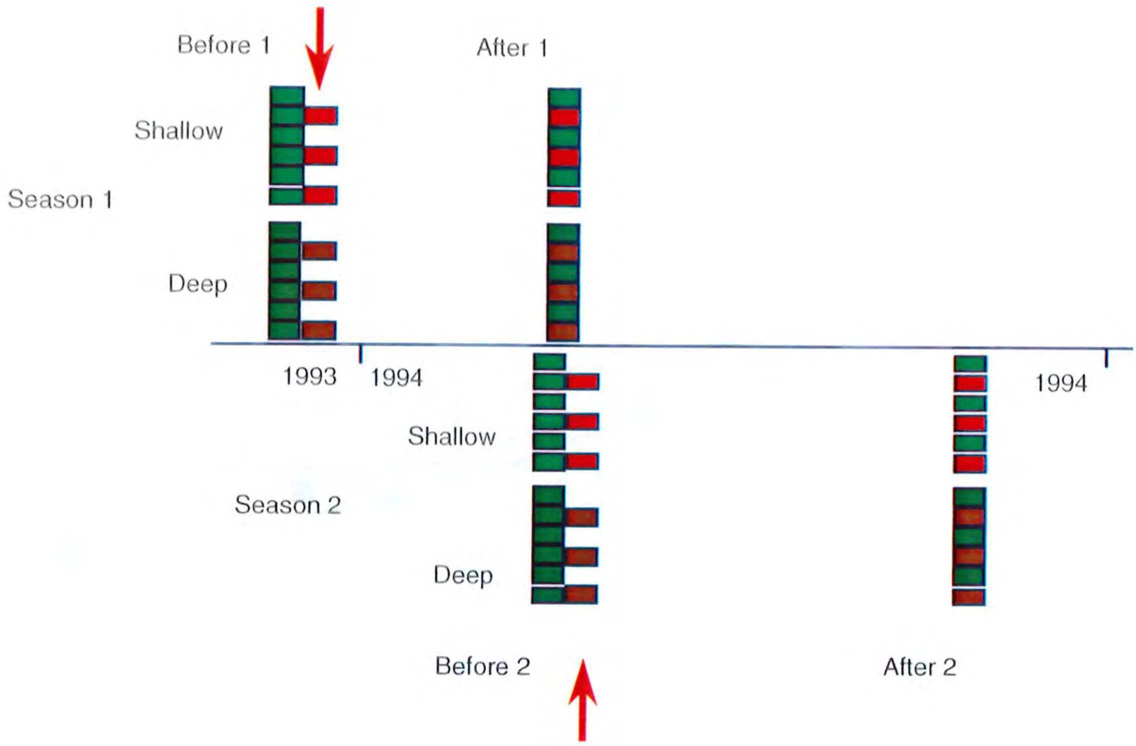

Figure 4.03 Timeline for sampling and manipulation of plots. Arrows show timing of the application of the trawling to the treatment plots.

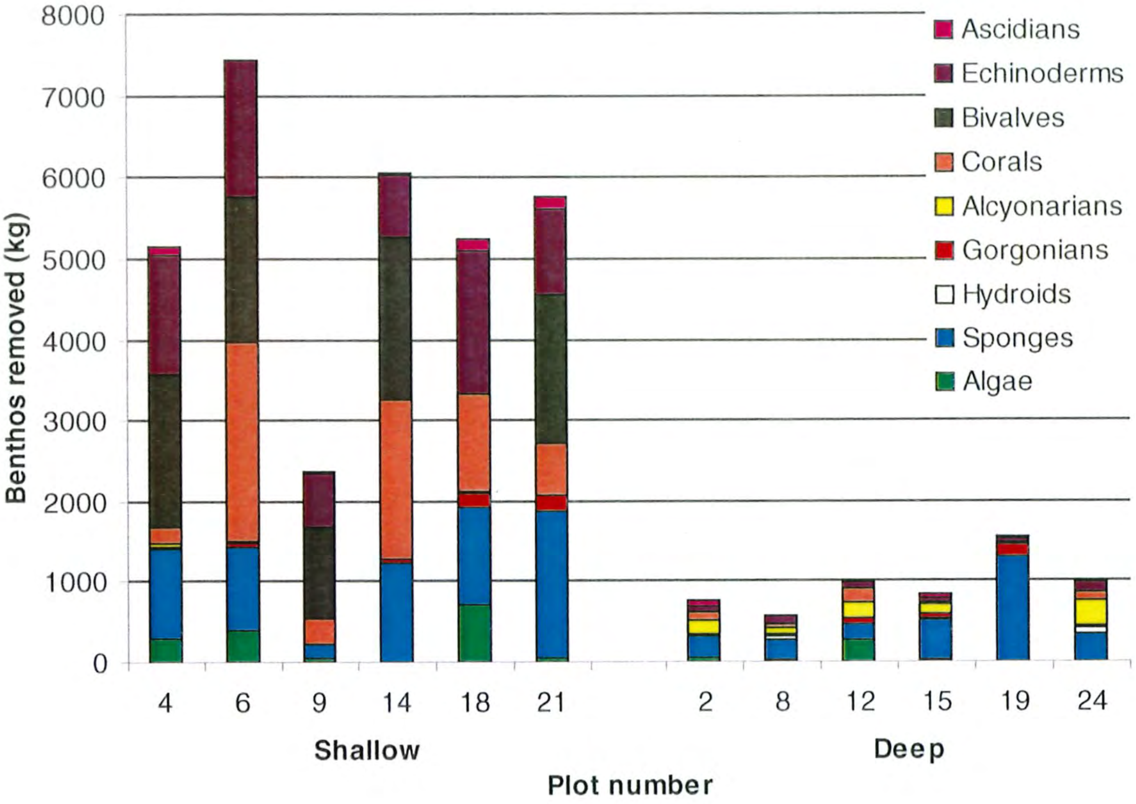

Figure 4.04 The amount of benthos material, by benthos class, removed from manipulated plots by both trawlers during the experimental trawling impact phase.

APPENDIX 4 A

Variances, cost-benefit analysis, and anticipated minimum detectable differences (δ) at the class and species level for taxa sampled by the benthic dredge, prawn trawl, and fish trawl in proposed experimental manipulations (assuming a negative impact of trawling exists) with Design: Season (wet,dry) by Habitat (shallow,deep) by Impact (control, trawled), 24 of 1.56×0.66 n.mile plots, 3 plots/combination, 3 stations/plot, $n'=12$, power $1-\beta=0.80$, $\alpha=0.05$, $\nu_1=1$, $\nu_2=16$, non-cent $t=\gamma=2.599$ — Note, the corresponding non-central $F=\lambda=6.753$). Level means and δ are reported in $\log_{10}$(gms) units; the effect size is also presented as (back-transformed) impact/control biomass ratio (%).

Taxa Benthic Dredge Classes	S^2stat	S^2loc	cost benefit stn/loc	Plot s^2	δ	Before & control	biomass ratio %
Sponges	1.582	0.0585	8.382	1.055	1.090	2.909	8
Hydrozoa	0.8301	0.2182	3.145	0.553	0.789	0.919	16
Octocorallian	0.4888	0.0237	7.329	0.326	0.606	2.100	25
Zoantharia	0.3363	0.1481	2.430	0.224	0.502	2.458	31
Cirripedia	0.0736	0.0809	1.539	0.049	0.235	-0.232	58
Decapoda	0.2074	0.0581	3.047	0.138	0.394	2.042	40
Gastropoda	0.2705	0.1107	2.520	0.180	0.450	1.903	35
Bivalvia	0.2387	0.4026	1.242	0.159	0.423	2.233	38
Cephalopoda	0.1229	0.0873	1.914	0.082	0.304	1.353	50
Bryozoans	0.9876	0.0218	10.848	0.658	0.861	1.712	14
Crinoidea	0.63	0.1764	3.047	0.420	0.688	2.393	21
Asteroidea	0.3957	0.4399	1.529	0.264	0.545	2.109	29
Echinoidea	0.9068	0.2517	3.061	0.605	0.825	1.893	15
Holothurioidea	1.2425	0.2495	3.598	0.828	0.966	2.205	11
Ophiuroidea	0.7095	0.0244	8.695	0.473	0.730	0.826	19
Ascidiacea	0.4197	0.1591	2.619	0.280	0.561	2.583	27
Average	0.524	0.163	3.771		0.592		27

Benthic Dredge species	Taxa	S^2stat	S^2loc	cost benefit stn/loc	Plot s^2	δ	Before & control	biomass ratio %
Octocorallia	Alcyonarian 1	0.8598	0.0626	5.974	0.573	0.803	0.704	16
Zoantharia	*Flabellum sp.1*	0.2991	0.1234	2.511	0.199	0.474	0.482	34
Zoantharia	*Fungia sp.1*	0.2749	0.1208	2.433	0.183	0.454	1.399	35
Zoantharia	*Sphaenopus sp.1*	0.5023	0.1799	2.694	0.335	0.614	1.698	24
Decapoda	*Portunus rubromargina*	0.6721	0.0813	4.636	0.448	0.710	0.769	19
Decapoda	*Portunus tenuipes*	0.1832	0.1191	2.000	0.122	0.371	0.928	43
Gastropoda	*Chicoreus cervicornis*	0.1424	0.1171	1.778	0.095	0.327	0.442	47
Bivalvia	*Amusium pleuronectes*	0.3277	0.0918	3.047	0.218	0.496	0.787	32
Bivalvia	*Melaxinia vitrea*	0.1602	0.1156	1.899	0.107	0.347	0.460	45
Crinoidea	Crinoid 15	0.4644	0.2762	2.091	0.310	0.590	1.002	26
Crinoidea	Crinoid 17	0.5669	0.0233	7.957	0.378	0.652	1.411	22
Crinoidea	Crinoid 5	0.2618	0.0906	2.741	0.175	0.443	1.679	36
Asteroidea	*Astropecten granulatus*	0.5093	0.1426	3.047	0.340	0.618	0.473	24
Asteroidea	*Astropecten sp.4*	0.418	0.117	3.047	0.279	0.560	0.211	28
Asteroidea	*Metrodira subulata*	0.5307	0.1405	3.134	0.354	0.631	0.148	23
Asteroidea	*Stellaster equestris*	0.7072	0.1408	3.614	0.471	0.728	1.099	19
Echinoidea	*Laganum sp.3*	0.8491	0.2378	3.047	0.566	0.798	0.829	16
	Average	0.455	0.128	3.274		0.566		29

Taxa **Prawn bycatch Classes**	**S^2stat**	**S^2loc**	**cost benefit stn/loc**	**Plot s^2**	**δ**	**Before & control**	**biomass ratio %**
Algae	0.0447	0.0003	19.245	0.030	0.183	0.649	66
Sponges	2.1101	0.3047	4.244	1.407	1.258	1.284	6
Hydrozoa	0.3552	0.0995	3.047	0.237	0.516	0.715	30
Octocorallian	0.5917	0.1248	3.511	0.394	0.666	0.615	22
Zoantharia	0.0814	0.0052	6.376	0.054	0.247	2.245	57
Polycheatea	0.0047	0.0004	5.416	0.003	0.060	0.000	87
Decapoda	0.0355	0.0718	1.134	0.024	0.163	1.652	69
Gastropoda	0.0042	0.0012	3.047	0.003	0.056	2.005	88
Bivalvia	0.1073	0.2521	1.052	0.072	0.284	1.970	52
Cephalopoda	0.2505	0.0298	4.676	0.167	0.434	0.949	37
Bryozoans	0.0047	0.0005	4.967	0.003	0.060	0.245	87
Crinoidea	0.3712	0.1039	3.047	0.247	0.528	0.395	30
Asteroidea	0.653	0.3131	2.329	0.435	0.700	-0.050	20
Echinoidea	0.2983	0.0853	3.016	0.199	0.473	0.681	34
Holothurioidea	0.5568	0.1559	3.047	0.371	0.646	0.296	23
Ophiuroidea	0.1409	0.0395	3.047	0.094	0.325	0.000	47
Ascidiacea	0.1918	0.0537	3.047	0.128	0.379	0.000	42
Average	0.341	0.097	4.368		0.411		47

Taxa **Prawn bycatch by species**		**S^2stat**	**S^2loc**	**cost benefit stn/loc**	**Plot s^2**	**δ**	**Before & control**	**biomass ratio %**
Decapoda	*Portunus rubromarginat*	0.1501	0.0626	2.497	0.100	0.336	1.783	46
Decapoda	*Portunus tenuipes*	0.2056	0.2138	1.581	0.137	0.393	1.721	40
Decapoda	*Thenus orientalis*	0.3492	0.2922	1.763	0.233	0.512	1.683	31
Bivalvia	*Amussiidae*	0.2105	0.1955	1.673	0.140	0.397	1.589	40
Cephalopod	*Sepioidae*	0.4323	0.1811	2.491	0.288	0.570	1.391	27
Pisces	*Apistus carinatus*	0.148	0.2008	1.384	0.099	0.333	1.609	46
Pisces	*Apogon ellioti*	0.2678	0.2311	1.736	0.179	0.448	1.216	36
Pisces	*Apogon fasciatus*	0.4783	0.1202	3.217	0.319	0.599	1.289	25
Pisces	*Callionymus grossi*	0.1769	0.1558	1.718	0.118	0.364	1.342	43
Pisces	*Choerodon cephalotes*	0.1996	0.15	1.860	0.133	0.387	1.756	41
Pisces	*Choerodon sp.2*	0.3986	0.045	4.797	0.266	0.547	1.623	28
Pisces	*Engyprosopon grandisq*	0.1859	0.2738	1.329	0.124	0.374	1.134	42
Pisces	*Euristhmus nudiceps*	0.045	0.2363	0.704	0.030	0.184	1.816	65
Pisces	*Lagocephalus sceleratu*	0.1849	0.0518	3.047	0.123	0.373	1.598	42
Pisces	*Lethrinus genivittatus*	0.0635	0.1238	1.155	0.042	0.218	3.270	60
Pisces	*Nemipterus furcosus*	0.072	0.0749	1.581	0.048	0.232	2.949	59
Pisces	*Nemipterus peronii*	0.2647	0.0741	3.047	0.176	0.446	1.750	36
Pisces	*Paramonacanthus choir*	0.1527	0.0838	2.177	0.102	0.339	1.914	46
Pisces	*Paramonacanthus japon*	0.1358	0.096	1.917	0.091	0.319	1.964	48
Pisces	*Pentapodus paradiseus*	0.4013	0.0204	7.153	0.268	0.549	2.139	28
Pisces	*Priacanthus tayenus*	0.3292	0.074	3.402	0.219	0.497	1.969	32
Pisces	*Pseudorhombus diplosp*	0.2779	0.0462	3.954	0.185	0.457	1.584	35
Pisces	*Pseudorhombus spinos*	0.4021	0.1634	2.530	0.268	0.549	1.404	28
Pisces	*Rhynchostracion nasus*	0.6316	0.1768	3.047	0.421	0.688	1.370	20
Pisces	*Saurida undosquamis*	0.1421	0.0343	3.284	0.095	0.326	2.363	47
Pisces	*Scolopsis taeniopterus*	0.1256	0.2137	1.236	0.084	0.307	2.250	49
Pisces	*Selaroides leptolepis*	0.5374	0.06	4.826	0.358	0.635	1.089	23
Pisces	*Siganus canaliculatus*	0.4513	0.1888	2.493	0.301	0.582	1.376	26
Pisces	*Sorsogona tuberculata*	0.1134	0.4883	0.777	0.076	0.292	1.019	51
Pisces	*Suggrundus isacanthus*	0.0838	0.0686	1.783	0.056	0.251	1.896	56
Pisces	*Torquigener pallimacul*	0.197	0.1035	2.225	0.131	0.384	1.721	41
Pisces	*Upeneus tragula*	0.2659	0.2274	1.744	0.177	0.447	2.635	36
	Average	0.253	0.148	2.441		0.417		40

Taxa	S^2stat	S^2loc	stn/loc	Plot s^2	δ	Before control	biomass ratio %
Fish Trawl by Families							
Clupeidae	0.9828	0.5885	2.084	0.655	0.859	1.370	14
Synodontidae	0.2301	0.1905	1.772	0.153	0.416	2.674	38
Fistulariidae	0.1923	0.126	1.992	0.128	0.380	1.889	42
Priacanthidae	0.2135	0.0598	3.047	0.142	0.400	2.503	40
Carangidae	0.6641	0.0612	5.312	0.443	0.706	3.482	20
Leiognathidae	0.2845	0.2252	1.813	0.190	0.462	2.831	35
Nemipteridae	0.333	0.2795	1.760	0.222	0.500	3.653	32
Gerreidae	0.2656	0.338	1.429	0.177	0.446	2.042	36
Lethrinidae	0.139	0.4289	0.918	0.093	0.323	4.092	48
Mullidae	0.485	0.4375	1.698	0.323	0.603	2.696	25
Labridae	0.6314	0.1521	3.286	0.421	0.688	2.395	20
Siganidae	0.4349	0.3521	1.792	0.290	0.571	2.605	27
Scombridae	0.3205	0.132	2.513	0.214	0.490	2.671	32
Balistidae	0.5739	0.1607	3.047	0.383	0.656	2.172	22
Tetraodontidae	0.4867	0.1005	3.548	0.324	0.604	2.646	25
Average	0.416	0.242	2.401		0.540		30

Fish Trawl by species	S^2stat	S^2loc	stn/loc	Plot s^2	δ	Before control	Biomass ratio %
Herklotsichthys lippa	0.2565	0.0718	3.047	0.171	0.439	1.400	36
Saurida undosquamis	0.2437	0.1689	1.937	0.162	0.428	2.670	37
Fistularia petimba	0.287	0.0881	2.911	0.191	0.464	1.546	34
Priacanthus tayenus	0.4428	0.124	3.047	0.295	0.576	2.105	27
Echeneis naucrates	0.5485	0.1536	3.047	0.366	0.642	1.537	23
Alepes sp.	0.3406	0.0954	3.047	0.227	0.506	2.378	31
Carangoides caeruleopi	0.3341	0.2245	1.967	0.223	0.501	1.974	32
Carangoides gymnostet	0.243	0.079	2.828	0.162	0.427	1.664	37
Carangoides hedlanden	0.337	0.0943	3.047	0.225	0.503	2.158	31
Carangoides humerosus	0.164	0.0092	6.792	0.109	0.351	2.047	45
Selar boops	0.5971	0.3261	2.182	0.398	0.669	2.138	21
Selaroides leptolepis	0.6741	0.1451	3.476	0.449	0.711	3.160	19
Leiognathus bindus	0.5253	0.3611	1.945	0.350	0.628	1.741	24
Leiognathus leuciscus	0.8364	0.0845	5.072	0.558	0.792	0.621	16
Leiognathus sp.	0.3786	0.2554	1.963	0.252	0.533	2.497	29
Nemipterus furcosus	0.4815	0.2199	2.386	0.321	0.601	2.929	25
Nemipterus hexodon	0.2928	0.0692	3.318	0.195	0.469	1.690	34
Nemipterus peronii	0.1084	0.1255	1.499	0.072	0.285	1.675	52
Pentapodus paradiseus	0.4222	0.3809	1.698	0.281	0.563	2.542	27
Scolopsis taeniopterus	0.2609	0.2806	1.555	0.174	0.442	1.737	36
Gerres oyena	0.3396	0.1513	2.416	0.226	0.505	1.906	31
Pentaprion longimanus	0.2354	0.2762	1.488	0.157	0.420	1.538	38
Diagramma pictum	0.8574	0.0141	12.593	0.572	0.802	1.960	16
Lethrinus genivittatus	0.1547	0.402	1.000	0.103	0.341	3.979	46
Upeneus luzonius	0.2063	0.288	1.365	0.138	0.393	2.114	40
Upeneus tragula	0.4092	0.1156	3.034	0.273	0.554	1.262	28
Pristotis jerdoni	0.391	0.0019	23.187	0.261	0.542	1.586	29
Sphyraena forsteri	0.687	0.1924	3.047	0.458	0.718	1.503	19
Choerodon cephalotes	0.4826	0.1338	3.063	0.322	0.602	2.009	25
Choerodon sp.2	0.5215	0.1319	3.206	0.348	0.626	1.728	24
Siganus canaliculatus	0.4447	0.3798	1.745	0.296	0.578	2.576	26
Rastrelliger kanagurta	0.1588	0.0445	3.047	0.106	0.345	2.092	45
Scomberomorus queens	0.1433	0.1439	1.609	0.096	0.328	2.828	47
Paramonacanthus japon	0.3713	0.0081	10.907	0.248	0.528	1.308	30
Lagocephalus sceleratu	0.3426	0.0832	3.272	0.228	0.507	1.800	31
Torquigener pallimacul	0.5601	0.1755	2.880	0.373	0.648	1.892	22
Average	0.391	0.164	3.740		0.527		31

Taxa	S^2stat	S^2loc	cost benefit stn/loc	Plot s^2	δ	Before & control	biomass ratio %
Prawns by species							
Metapenaeopsis palmen	0.1477	0.2337	1.282	0.098	0.333	-0.010	46
Metapenaeopsis rosea	0.3584	0.5122	1.349	0.239	0.519	-0.541	30
Metapenaeus endeavou	0.1364	0.3074	1.074	0.091	0.320	1.644	48
Penaeus esculentus	0.0325	0.1348	0.792	0.022	0.156	1.801	70
Penaeus latisulcatus	0.2129	0.1673	1.819	0.142	0.400	0.808	40
Penaeus longistylus	0.3482	0.1566	2.404	0.232	0.511	0.882	31
Trachypenaeus anchora	0.3538	0.1173	2.800	0.236	0.515	-0.766	31
Trachypenaeus granulo	0.4331	0.6469	1.319	0.289	0.570	-0.166	27
Average	0.253	0.285	1.605		0.415		40

CHAPTER 5

REPEAT–TRAWL DEPLETION

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CONTENTS

5 REPEAT–TRAWL DEPLETION

Objectives

To estimate the rate at which individual prawn trawls deplete benthos and to estimate the intensity of trawling that would cause substantial impact on benthos. These objectives were to be achieved as follows:

A series of accurately repeated trawls would be made along pre-specified tracks. The biomass and composition of the catch from each trawl were to be recorded. Because the depletion rate may vary between locations, multiple trawls were to be carried out on a number of chosen tracks aiming for an even number of tracks in deep and shallow plots. Video recordings would be made of the footrope in order to observe and understand the fate of benthos as it encounters the trawl gear.

5.1 Introduction

Trawling is frequently cited as having negative impacts on benthic communities, mainly through removal of sessile epifauna such as sponges and bryozoans as well as biogenic structures such as polychaete tubes (Dayton et al., 1995). Trawling also removes mobile but slow moving fauna like echinoderms and molluscs (Chapter 2). Attempts to quantify the effects of trawling have been made using two basic approaches. Firstly to compare presently fished areas with the same areas before they were fished. Secondly to compare fished areas with areas that are not fished. Both of these approaches have difficulties because of the difficulty of finding suitable areas to monitor, as indicated by the paucity of published studies comparing areas open and closed to fishing.

Comparisons of the present condition of heavily fished areas with the condition at some time in the past have been confounded by changes unrelated to fishing. Riesen and Reise (1982) for example examined the macrobenthos of the Waddensea after 55 years and found major differences but only one of these – the disappearance of reefs formed by a colonial polychaete – could be ascribed to trawling. Of the other significant changes, oyster beds had disappeared due to overexploitation by fishing methods other than trawling, mussels had increased because of cultivation and Zostera had been wiped out by disease. Where information is available on the intensity of fishing and areas of known differences of fishing are available, it is possible to use fishing intensity as a factor. This approach has been adopted for example by Collie et al. (1996) in estimating the effects of scallop dredging on the seabed fauna of Georges Bank in the North West Atlantic. There is a danger in this approach if the seabed is first surveyed and the intensity of fishing is then deduced from the condition of the epibenthos since factors other than fishing also affect the distribution of seabed fauna.

If an area previously closed to fishing is available, then an alternative approach is to use manipulative experiments in which an area is surveyed, then subjected to a known trawl impact and resurveyed. This is the basis of the BACI (Before-After-Control-Impact) experiment which has been used by several researchers for estimating impacts of trawling (see Thrush et al., 1995). Van Dolah et al. (1987) used a modification of this approach. This is a useful technique provided certain statistical constraints are taken into account (Underwood, 1994). The BACI experiment that we carried out in the Green Zone (Chapter 4) has exposed a practical difficulty associated with implementing the technique. If the impact of a single trawl is not large, then it may not be possible to detect an impact when the benthic environment is highly variable – a situation common in many tropical and subtropical areas. Increasing the impact by multiple trawl coverage may not be feasible given the large scale of the experiments. In our case, a single impact trawl over the 12 plots together with the before and after monitoring of 24 plots required over 700 hours of trawling. The results suggest that several trawl coverages of the impact plots would have been required to generate a measurable impact and it would have taken about one year of effort by the 2 research vessels. A second problem with measuring the impact of a single pass of a trawl, is that impacts are cumulative and differential. Some species may be severely impacted by a single trawl. Sainsbury et al. (1992) found that a single pass of a fish trawl had a 90% impact on large sponges on the North West Shelf of Australia. Other species may be able to withstand one, two or three trawls but their vulnerability increases with successive trawls. This means that the impact of repeated trawling is not simply a power cumulative relationship.

A manipulative experimental approach that monitors the effect of multiple trawls is to repeatedly trawl an area that has previously not been trawled. This approach enables the depletion rate to be estimated from the sequence of catches, as well as being more likely to produce a measurable impact in Before-After comparisons. There are two important constraints to this approach and they both relate to the application of the trawl effort to the experimental area. The first is that the amount of trawl effort is high and consequently it is usually not feasible to use large areas because of costs. This makes edge effects important and may limit the experiment to determining the impacts on sessile or near sessile species. The second constraint is that the impact has to be applied very accurately. This has been a major drawback of repeat trawling experiments in the past because it has not been feasible to replicate trawl tracks or to know the exact position of the gear on the bottom sufficiently accurately to quantify the impact. The availability of Differential Global Positioning Systems (DGPS) with an accuracy of a few metres combined with plotter and sonar survey techniques has made accurate position fixing possible. McKeown and Gordon (1997) have described the technique in a major study of the impacts of otter trawls on a sandy seabed habitat (Gordon et al., 1997). Even with accurate position fixing, it is still difficult to ensure that the impact gear (trawl or dredge) is following the desired path. In this respect, the relatively wide prawn trawl (22m) that we towed in our experiments gave a high probability of achieving overlapping tracks.

We adopted a similar approach to estimating the effect of repeated trawling on seabed epifauna in the inter-reef area of the northern Great Barrier Reef (GBR). A large commercial trawl fishery for penaeid prawns has traditionally fished the lagoon between the GBR and the mainland. In the 1980s, an additional species, *Penaeus longistylus*, began to be targeted. This species is associated with coral reefs. The juveniles live on the reefs and the adults are found in the channels between and adjacent to reefs. The introduction of accurate satellite navigation systems and colour echosounders enabled trawlers to fish near to reefs and around obstructions. The possible impacts of this inter-reef trawling raised concerns and the GBR Marine Park Authority decided to support a research project that would quantify the impact of prawn trawling on the seabed. Part of the approach was to carry out a repeat trawl experiment in an area that was closed to fishing in the northern GBR. The area, known as the Green Zone because of its zoning classification, is located between about 11°15' and 11°45'. Oficially the area is designated the Far Northern Cross Shelf Closure. It has been closed to fishing since 1985. Although trawling had been allowed there prior to the closure, trawling at that time had been confined to the inshore lagoon because the inter-reef area was, and still is, uncharted and because accurate position fixing was not available.

We took advantage of the plots that had been established in the BACI experiment (see Chapter 4). These offered areas that were known to be trawlable and had no record of previous trawling other than the single trawl of the BACI experimental treatments. They had also been intensively surveyed by video sled, benthic dredge, and prawn trawl and fish trawl.

5.2 Methods

5.2.1 Design of repeat-trawl depletion experiment

When designing the repeat-trawl experiment, our prior knowledge of the benthos depletion rate per trawl was limited. We had compared the density of benthic material collected in prawn trawl samples during the BACI experiment with the density from benthic dredge samples (Table 4.10 in Chapter 4), using the ratio of total biomass to total swept area to estimate density. From this analysis, a depletion rate of 5–10 percent appeared likely for most organisms.

We expected to have 12 days for conducting the repeat-trawl experiment. Estimating a low removal rate such as 10 percent would require many trawls on each track given the likely level of variation in catches, and would restrict the repeated trawls to a few tracks. But if the removal rate was high (50 percent or more per trawl), we would need to conduct only a few trawls per track and would be able to conduct repeated trawling on more tracks. We designed the depletion study to make optimal use of resources whether the rate was high (for example, 50 percent) or low (for example, 10 percent). The first six days were used to obtain information to decide on resource allocation for the next six days. During the first six days of the experiment, one day was to be spent conducting repeated trawls on each of six tracks. The entire catch from each trawl was to be sorted, to minimise sources of variation in the analysis. Large items were identified and weighed before being discarded, and the rest of the catch was sent to the Cleveland laboratory for processing.

The available set of tracks consisted of six in deep plots and six in shallow plots. Three deep and three shallow tracks were chosen for the first six days. This would provide data for estimating the average depletion rate (π) on each track and the predicted number of trawls to achieve 90 percent depletion on such tracks. If the preliminary estimates of the depletion rate were (50 percent or more) and well defined (standard error below 5 percent), we would spend the remaining six days trawling six more tracks. In fact the preliminary estimates of depletion rates were low (average of 8 percent across tracks) with a large standard error (average of 9 percent), so for the second six days available we returned to the same six tracks for a second day of trawling on each track.

Data model for depletion study

We needed a conceptual model relating catch to trawl intensity in order to assess the adequacy of the design to address the objectives of the study. The main objective was to estimate the mean depletion rate, π, on a number of tracks with good precision.

The catch can be described by the well-known model associated with the Leslie-Davis method (Hilborn & Walters, 1992) of estimating populations from depletion studies. The basic model is as follows:

$$C_i = q_i(X_o - T_{i-1})$$

where

C_i is the biomass for the i'th trawl;

q_i is the proportion of the available benthos caught in the i'th trawl;

X_o is the total benthos present before trawling begins; and

T_{i-1} is the total amount caught before the i'th trawl begins.

In an ideal world, trawls sould repeatedly cover exactly the same ground and the removal rate would be constant for all trawls on a given track. We recognised that the *Gwendoline May* would deviate from the intended path for each trawl of a given track, and that the efficiency of the trawl gear on a given track could vary. However, we had no prior information about the level of variation that would arise from these two sources, other than that they would increase the 'noise' in the sequence of catch data on each track.

As a planning tool, we used the above model to describe the pattern of catch with repeated trawls and incorporated extra variation to simulate the two unknown sources of error by allowing the parameter q to vary independently from trawl to trawl, about a common mean value π with a constant variance.

The catch would comprise a number of species, so it was more relevant to model the biomass than the number of items present. As a result, we assumed that the q-values could fall anywhere on the scale from 0 to 1. In other words, the q-values (and hence the catch) needed to be modelled by a continuous distribution rather than a discrete distribution.

One choice of distribution for the q-values was the beta distribution, which is as follows:

$$\text{prob}(q_i) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} q_i^{(\alpha-1)}(1-q_i)^{(\beta-1)}$$

Here, Γ () is the gamma function. The parameters α and β were assumed to be constant for a given track, but possibly different between tracks. The mean and variance of q for a given track are functions of α and β, as given below. Note that they can instead be expressed in terms of α and π, which aids interpretation: π is the expected (or mean) depletion rate for the given track, and α controls the dispersion (or variance) in depletion rates between trawls. The larger the value of α, the smaller the variability in q-values.

The mean depletion rate is as follows:

$$\text{mean}(q_i) = \frac{\alpha}{\alpha+\beta} = \pi$$

The variance in q is as follows:

$$\text{variance}(q_i) = \frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)} = \frac{\pi^2(1-\pi)}{(\pi+\alpha)}$$

The design of the study meant that there would be at least 6 trawls per track and up to 16 trawls – depending on whether 6 or 8 trawls were achieved per day. A simulation study was carried out to assess the mean impact level (or cumulative depletion) that would be achieved after 6, 8, 12 and 16 trawls. The mean depletion rate, π, was assigned one of four values: 10, 20, 30 or 50 percent. A value for the dispersion parameter, α, was chosen so that the variance of q would correspond to a coefficient of variation – s.d.(q)/mean(q) of approximately 20% ('low'), 30% ('medium') or 50% ('high') In the actual experiment, the coefficient of variation for q was often as high as 100% especially for estimated depletion rates under 5%. Table 5.01 shows the mean cumulative depletion that should be achieved on tracks with a given mean depletion rate. For π of 30 percent or more, one day of trawling should reduce the sessile benthos by an average of at least 88 percent. For lower values of π, two days of trawling should achieve a substantial depletion.

The overall depletion could be expected to vary widely from track to track, or trawl to trawl on the same track, depending on whether q was highly consistent between repeated trawls on the same track (low variance) or highly variable (high variance). Estimates of the impact level would be more variable than this, because the initial biomass was not known beforehand and would have to be estimated.

Table 5.01 Mean and standard deviation of actual cumulative depletion from simulations of four levels of trawl effort and 12 combinations of mean depletion rate and variation of depletion rate across trawls.

True mean depletion rate π (percent)	Number of trawls	Mean cumulative depletion (percent)	Standard deviation of cumulative depletion (percent)		
			Low variance	Medium variance	High variance
10	6	46.9	3.1	4.3	6.8
	8	57.0	2.9	4.0	6.4
	12	71.8	2.3	3.3	5.1
	16	81.5	1.7	2.5	3.9
20	6	73.8	3.2	5.1	8.2
	8	83.2	2.4	3.7	6.1
	12	93.1	1.2	1.9	3.1
	16	97.2	0.6	0.9	1.5
30	6	88.2	2.3	4.2	6.5
	8	94.2	1.3	2.4	3.8
	12	98.6	0.4	0.7	1.2
	16	99.7	0.1	0.2	0.3
50	6	98.4	0.6	1.3	2.2
	8	99.6	0.2	0.4	0.7
	12	100.0	< 0.1	< 0.1	0.1
	16	100.0	< 0.1	< 0.1	< 0.1

Fieldwork in the Far Northern GBR and sorting of catch

Trawls were repeated very accurately along three deep (~ 35 m) tracks and three shallow (~ 20 m) tracks. The repeat-trawl tracks were in the same part of the Closed Zone as the BACI experiment: the mid-shelf inter-reef/shoal stratum. Tracks were chosen inside the BACI plots because this took advantage of knowledge about the distribution of structural benthos that had already been collected in video surveys. In this way, it was possible to choose tracks where the trawler would encounter a number of typical patches of sponges, gorgonians and corals but would avoid "reefy" tracks that would not normally be fished.

The repeat-trawl depletion experiment was carried out with a 12 fathom "Florida Flyer" prawn trawl net towed by the *Gwendoline May*. Trawls were made in daylight, as the main "target" was sessile benthos and daylight was required for the video surveys, which were interspersed among the trawls.

It was important to trawl very accurately along each specified track, so differential GPS (accuracy ~3m r.m.s.) was used for navigation, and positions were recorded electronically every two seconds while the boat was trawling each track. On one of the first tracks to be trawled, a series of 8 marker buoys (30 m from the centre line of the boat) was deployed either side of the initial trawl to assess the effectiveness of navigation. The buoys set up a lane through which the subsequent trawls passed without picking up any of the buoys.

A single 12 fathom (22 m) prawn trawl net was towed behind the boat. The seams along the bottom panel of the net were reinforced with rope 20 mm in diameter. This rope was attached to the ground chain at the trawl (otter) boards.

Video footage was obtained before, during and after the trawling. A video sled was hauled down each track before trawling began, then after the third and seventh haul to observe the extent of the impact.

The process of identifying, counting and weighing the catch in detail was carried out either on-board or later at the Cleveland laboratory, depending on the nature of the catch. Bulky items that could be identified on-board were counted (where appropriate) and weighed on a balance scale accurate to 100 g and discarded. Because of time constraints in the field, the numerous smaller items could not be processed on-board; these items were packed up, frozen and freighted to Cleveland to be processed.

5.2.2 Distribution of trawls and video transects on tracks

Differential Global Positioning Satellite (DGPS) data were used to map out the intensity distribution for trawls by taking the longitude and latitude of the trawler's antenna every two seconds along the track of each trawl.

To set up a more convenient unit of measurement (metres), the longitude and latitude were converted as follows. The longitudes were multiplied by the cosine of the mean latitude of the tracks (about 0.98 at latitude 11°S), then both longitude and latitude were converted to metres using the conversion: 1' = 1850.3 m.

Another transformation of coordinates was carried out to set up a more convenient frame of reference for graphical presentation. Because the tracks deviate only slightly from a straight line, we defined a coordinate system (x, y) with the x axis parallel to the track and the y axis perpendicular to the track. The new positions were calculated from principal components of the two-column matrix of DGPS data representing the path followed by the boat. The x component was the score of the first principal component (along track), and the y component was the score of the second principal component (cross-track). We then linearly interpolated the trawl's y-position onto an x grid with uniform spacing of 10 m. Linear interpolation was adequate because consecutive DGPS positions were about 3–4 m apart.

The trawl-intensity distribution was calculated in the following way. We defined a grid of (x, y) points on which to compute the trawl coverage. The grid had a y spacing of 1 m, an x spacing of 10 m and was typically 60 m wide in the y-direction. The swept path of the trawl net was assumed to be 18 m.

In mathematical terms we obtained the trawl intensity coverage, $C(x,y)$, at each point on this grid by applying a uniform kernel density ($k(z)=1$ for $|z|<½$, $k(z)=0$ otherwise) to the cross-track distances $y_i(x)$ for each value of the along-track distance x thus,

$$C(x,y)=\sum_{i=1}^{n} k\left(\frac{y-y_i(x)}{w}\right)$$

where n is the number of trawls and w is the width of the net.

Using this data, we produced a series of maps showing the spatial intensity of trawling along each track. This information was used to check the extent to which the repeated trawls overlapped and the areal coverage of the depleted swath.

5.2.3 Statistical analysis of biomass depletion

For the depletion experiment, the primary source of data on benthos removal was the catch data itself: species composition, counts (where appropriate) and weights. Analysis of this data set is presented in this report. For the depletion experiment, the entire catch from all hauls was processed. Where a large quantity of a particular class (for example, algae) was found and was sufficiently complex to need processing at Cleveland, a portion of that class was shipped and the total on-board weight of the class was recorded.

Some statistical pre-processing of catch data was required because some items were weighed on board ("wet" weights) while others were frozen on board and shipped back to Cleveland to be processed ("defrosted" weights). During freezing/thawing, animals tended to lose water. At Cleveland they were defrosted by being immersed in water, which replenishes the lost water to an extent, but in a number of cases the resultant "defrosted" weight probably differed markedly from the "wet" weight. We developed a statistical calibration to correct for this water loss. The method we used for doing so is described in Appendix 5.A.

As in previous reports, species were grouped in order to provide a reasonably succinct interpretation of the data. Another benefit of grouping is that the number of animals in a sample increases and there are fewer trawls with zero abundance. This should enhance the quality of models fitted to the trawl-depletion data.

Benthos were grouped into classes. The following classes were considered to be sessile: algae, alcyonarians, ascidians, bryozoans, gorgonians, hydrozoans, sponges (porifera) and zoantharians. The remaining classes were considered to be mobile: asteroids, bivalves, cephalopods, crinoids, crustaceans, echinoids, gastropods, holothurians and ophiuroids.

Fish were grouped into guilds that reflected the most common position of the species in the water column together with the main component of their diet. Water-column position was selected from three categories: pelagic (usually swimming in the water column and not near the sea bed); benthic (closely associated with the sea bed and usually stationary on it); or bentho-pelagic (closely associated with the sea bed but usually in the water column above it). Diet was selected from five categories: piscivorous (at least 70% fish prey); herbivorous (at least 70% plant material); planktivorous (at least 70% small planktonic organisms); invertebrate-feeding (at least 70% invertebrates associated with the sea bed); or mixed (no single food source dominating). Species lists, showing guild membership, are given in Appendix 5.B.

The depletion data for each track were graphed according to the Leslie–Davis approach (Hilborn and Walters, 1992). The value on the X-axis represents the cumulative catch for all previous trawls and the Y-axis represents the catch from each individual subsequent repeat trawl. A regression line was then fitted to the data from each track.

Effect of variation in trawl position on estimate of depletion rate

Although the trawling was very accurate, it was not possible for repeated trawls on a given track to cover exactly the same ground each time. This means the estimated depletion rate would be systematically lower than the true depletion rate. The actual trawl positions recorded every two seconds for the six tracks were used to assess the extent of this bias, using two simulation methods. The same basic framework was used for the two methods. The only difference was the distributions used to characterise initial ('virgin') biomass and the depletion rate of each trawl.

The framework consisted of setting up, for each track, a transect of dimensions similar to the length of each track and the full width of trawl coverage. Each transect was gridded into small cells and an initial biomass was allocated to each cell. The catch for the first trawl was set to zero initially. Then the first trawl was 'run' along the transect. If a cell lay within the path of this trawl, its biomass was depleted by q_1 percent. The trawl catch was augmented with the depleted biomass from that cell. By the end of the transect, the depleted biomass from all trawled cells had been accumulated into a total for that trawl. Then the second trawl was 'run' along the transect, with catch set to zero before the run. During the run, this trawl encountered some untrawled cells and some cells that had already lost q_1 percent of their biomass. Each cell lying in the trawl path was depleted by proportion q_2 percent, and the trawl catch was augmented with the depleted biomass of each cell it encountered. The procedure was repeated for thirteen trawls on each transect.

The transect used for each track was 1.2 n.mile long and 0.06 n.mile wide, using the coordinate system defined in Section 5.1.2. The transect was trimmed by 0.3 n.mile to simplify data handling at the ends, where records tended to become irregular in spacing due to changes in speed. Next the transect was partitioned into cells 0.005 n.mile (~ 9 m) long by 0.00025 n.mile (~ 45 cm) wide: 240 cells along the transect and 240 cells across the transect. The length of cells was as short as possible while ensuring that there would be at least one record of the boat's position along the Y-axis (cross-transect) for every cell. If more than one record was present, the average position was used. The width of cells was small enough to fit 20 cells across the path of a single trawl and to allow discrimination between the paths of different trawls on that transect.

For the first simulation method, the depletion rate of all trawls (q_1, q_2, q_3, ..., q_{11}, q_{12} and q_{13}) was set to 10 percent. The initial biomass of every cell was set to 100 gms. After running the simulation, the trawl catch data set was analysed using the Leslie-Davis method. Figure 5.01 shows the relationship between catch and cumulative prior catch for the six tracks. The data lies close to a straight line, but there is a small amount of deviation about this line. There are small jumps in the catch at intervals, as a trawl covers new ground not visited by previous trawls. The estimated depletion rates (Table 5.02) are all below 10 percent, with an average of 7.48 percent. Track 12 has the largest bias, being about one third smaller than the true depletion rate. Track 21 has the smallest bias, being about one sixth smaller than the true depletion rate. This simulation indicates that q-values actually obtained should be corrected by a factor of 1.33.

Table 5.02 Depletion rate estimates obtained from simulations of trawl runs with a 'fixed' rate per trawl and a 'random' rate per trawl, using actual trawl tracks but simulated biomass distribution

Track	p-value for 'fixed' method	Estimate of 'fixed' method depletion rate (percent)	Mean estimate of 'random' method depletion rate (percent)	Std deviation of 'random' method depletion rate (percent)
4	$< 10^{-9}$	7.81	9.73	4.29
12	$< 10^{-6}$	6.40	7.16	2.77
15	$< 10^{-9}$	7.70	8.58	2.41
18	$< 10^{-9}$	7.24	7.39	2.69
19	$< 10^{-8}$	7.46	7.47	2.22
21	$< 10^{-9}$	8.26	8.49	2.67

For the second simulation method, the depletion rate of all trawls ($q_1, q_2, q_3, \ldots, q_{11}, q_{12}$ and q_{13}) was allowed to vary about a mean of 10 percent. The variation was achieved by drawing random values from a beta-distribution, with parameter settings $\pi = 0.1$ and $\alpha = 10$ (as described in Section 5.2.1). The mean depletion rates from the experiment were in the range 7–10 percent. The initial biomass of each cell was drawn from a $\log_{10}$-normal distribution with mean $\mu = 2$ and $\sigma = 0.2$, giving a mean biomass of just over 100 gms per cell. The estimates of initial biomass from the experiment are of this magnitude. For this method, 100 simulations of 13 trawls were run for each track. After each simulation, the trawl catch data set was analysed using the Leslie-Davis method. Figure 5.02 shows the relationship between catch and cumulative prior catch for one simulation on each of the six tracks. This time the catch varies much more about the best-fit regression line, in a manner consistent with the real catch data presented in the results (Section 5.3.3). The estimated depletion rates (Table 5.02) are all below 10 percent, with an average of 8.14 percent. Once again, track 12 has the largest bias and track 21 the smallest bias. This simulation indicates that q-values should be corrected by a factor of 1.22.

The 600 depletion rates obtained from the second simulation method were used to assess whether the estimates differ significantly from the true mean rate of 10 percent. The depletion rates for each track had a near-normal distribution. A one-way analysis of variance, with track as the grouping factor, was applied to the difference between these rates and the true mean depletion rate. The average difference of −1.85 percent was highly significant (F ratio of 11.0; 5 and 594 degrees of freedom; $p < 0.0001$). In other words, depletion rates from analysis of repeated-trawl data need to be increased by about 25 percent to correct for the effect of variation in trawl position.

The depletion rates from the second 'random' simulation method were then compared with the values obtained from the first 'fixed' method, where only the trawl tracks were allowed to vary according to the actual records, but the depletion rate was fixed at 10 percent and the initial biomass was fixed at 100 gms per cell. A one-way analysis of variance, with track as the grouping factor, was applied to the difference between the 'random' rates for each track and the single 'fixed' rate for that track. The average difference of +0.66 percent significant (F ratio of 5.7; 5 and 594 degrees of freedom; $p < 0.0001$). In other words, a simple simulation that uses a fixed depletion rate and assumes biomass is evenly distributed over the entire transect will probably provide an over-estimate of the amount of bias caused by variation in trawl position.

Apart from variation in trawl position, two other factors will affect the estimate of the depletion rate. The depletion estimate is based on what is caught, hence the rate estimate could be larger than the actual rate if there are many benthic organisms that, by virtue of their size and growth habits, are impacted, dislodged or killed but never caught in a trawl net. Furthermore, the efficiency of the net is unlikely to remain constant: it almost certainly varies with terrain, tides and currents, and usage/storage patterns. Therefore the Leslie–Davis depletion rate is an estimate of the average rate at which prawn trawl nets may remove epibenthos and fish communities but there is probably considerable variation around this mean depletion rate.

5.3 Results

5.3.1 Distribution of trawl intensity

Figure 5.03 shows the overall intensity of trawling achieved on each of the tracks. The tracks are in reality almost straight, covering a distance of about 2700 m each, with maximum deviations of about 50 m from the central line. The graphs have accentuated these deviations because the horizontal axis is highly compressed. The intensity levels have been grouped to show areas trawled up to 5 times, areas trawled between 6 and 9 times, and those trawled between 10 and 13 times. Each track is generally about 30 m wide. The general trawl-intensity pattern is a central track between 11 m and 14 m wide that was trawled at least 10 times, and a track between 17 m and 19 m wide that was trawled at least 6 times.

For track 4, the intensity profile across the track at 200 m intervals is shown in Figure 5.04. The trawls on the end sections of the track (where the gear was being shot away or hauled) were less tightly aggregated than for the rest of the track. The width of the track that was trawled at least 10 times varied from 9 m to 14 m in width, and the width of the track trawled at least 6 times varied from 17 m to 19 m. The fullest width of the trawled area varied from 25 m to 35 m, but was mostly about 30 m wide.

For track 12, the intensity profile across the track at 200 m intervals is shown in Figure 5.05. The trawls were less tightly aggregated at one end. The width of the track that was trawled at least 10 times varied from 10 m to 14 m in width, and the width of the track trawled at least 6 times varied from 17 m to 21 m. The trawled area was generally less than 40 m wide.

For track 15, the intensity profile across the track at 200 m intervals is shown in Figure 5.06. The trawls were less tightly aggregated some distance from one end (between 400 m and 600 m from the centre). The width of the track that was trawled at least 10 times varied from 9 m to 13 m in width, and the width of the track trawled at least 6 times varied from 17 m to 21 m.

For track 18, the intensity profile across the track at 200 m intervals is shown in Figure 5.07. The width of the track trawled at least 10 times varied from 8 m to 13 m in width, and the width of the track trawled at least 6 times varied from 17 m to 20 m.

For track 19, the intensity profile across the track at 200 m intervals is shown in Figure 5.08. The trawls were less tightly aggregated at both ends. The width of the track trawled at least 10 times varied from 11 m to 14 m in width, and the width of the track trawled at least 6 times varied from 17 m to 19 m.

For track 21, the intensity profile across the track at 200 m intervals is shown in Figure 5.09 The trawls were less tightly aggregated at both ends. The width of the track trawled at least 10 times varied from 11 m to 16 m in width, and the width of the track trawled at least 6 times varied from 17 m to 19 m.

Figure 5.10 to 5.15 show the intensity profile after 7 trawls, and the tracks for the boat when towing the video sled before the trawls and after the third and seventh trawls. Generally, the video was towed inside the most heavily trawled area. For track 4 (Figure 5.10) the video sled was towed slightly off-centre for the third quarter of the track. For track 12 (Figure 5.11) the course followed by the second video tow deviated from the area trawled by the first seven trawls, about 100 m from the end of the track. The largest deviations occurred on track 18, where the pre-trawl video was poorly placed with respect to the trawled track in the first half of the track and at the end of the track.

5.3.2 Composition of total catch for each track

Table 5.03 shows the total catch over 13 trawls from each track, partitioned into benthic classes and fish guilds. The benthic classes (including algae) have been grouped into sessile and mobile organisms.

For all sessile organisms, nearly twice as much was caught on shallow tracks as on deep tracks (averages of 569 kg and 328 kg per track respectively in Table 5.03). The classes that were much more abundant on shallow tracks were ascidians, zoantharians and algae—together they accounted for nearly 70 percent of the total sessile weight. Two classes were more abundant on deep tracks: sponges and bryozoans. These depth preferences are in good agreement with results from the BACI experiment. On deep tracks, sponges (Porifera) accounted for 82 percent of the total sessile weight, whereas on shallow tracks they accounted for 34 percent—though still the largest class by weight.

In terms of mobile species, the difference between shallow and deep tracks was even more marked (averages of 767 kg and 58 kg per track respectively in Table 5.03). The main organisms responsible for this marked difference were the holothurians and bivalves. These accounted for nearly 70% of the total weight of mobile benthos on shallow tracks. On deep tracks, the weight of these two classes amounted to 2–3 percent of the weight found on shallow tracks.

Table 5.03 Total catch (kg) from 13 trawls on each track, grouped into sessile and mobile invertebrates and fish

	Shallow Tracks				Deep Tracks			
Class	4	18	21	Mean	12	15	19	Mean
All sessile	**678.5**	**587.0**	**440.5**	**568.7**	**314.0**	**129.1**	**539.9**	**327.7**
Algae	43.3	165.9	103.9	104.4	12.3	8.6	0.9	7.3
Porifera	236.7	126.0	211.0	191.2	250.0	73.4	479.8	267.7
Hydrozoa	0.7	1.2	2.2	1.4	1.5	2.6	0.3	1.4
Gorgonacea	5.5	6.5	5.8	6.0	3.8	3.5	12.4	6.6
Alcyonaria	3.8	38.8	3.0	15.2	13.6	6.7	6.3	8.9
Zoantharia	46.1	154.6	67.1	89.3	3.1	2.1	0.7	2.0
Bryozoa	2.1	7.1	4.6	4.6	17.5	5.4	15.0	12.7
Ascidia	340.5	86.8	42.9	156.7	12.1	26.8	24.5	21.2
All mobile	**977.1**	**842.1**	**361.1**	**726.8**	**63.7**	**68.9**	**40.3**	**57.7**
Crustacea	9.9	4.5	4.2	6.2	5.5	6.8	9.9	7.4
Bivalvia	237.9	326.6	15.2	193.2	0.4	11.9	0.4	4.3
Gastropoda	9.6	17.6	3.6	10.2	10.7	10.2	3.9	8.2
Cephalopoda	0.5	2.0	2.4	1.6	2.5	1.9	1.4	1.9
Asteroidea	42.6	27.6	81.9	50.7	12.0	12.0	15.1	13.0
Crinoidea	45.5	17.7	7.8	23.7	4.9	6.0	1.6	4.2
Echinoidea	5.3	1.5	4.4	3.8	4.1	2.1	2.0	2.8
Holothuradea	621.6	444.1	240.4	435.4	21.1	16.6	4.9	14.2
Ophiuroidea	4.3	0.6	1.4	2.1	2.5	1.3	1.2	1.6
All fish (in guilds)	**208.9**	**203.4**	**184.1**	**198.8**	**66.9**	**92.0**	**332.1**	**163.7**
Benthic–invertebrate	68.8	6.5	103.8	59.7	2.8	9.0	23.1	11.6
Benthic–mixed	0.3	0.8	0.1	0.4	0.1	0.1	1.0	0.4
Benthic–piscivorous	2.1	1.5	1.2	1.6	1.7	1.7	2.8	2.1
Benthopelagic–herbivorous	11.1	1.8	0.3	4.4	0.1	0.1	6.9	2.4
Benthopelagic–invertebrate	117.7	159.4	67.7	114.9	57.9	71.9	226.6	118.8
Benthopelagic–mixed	7.1	25.5	3.0	11.8	4.0	9.1	26.0	13.0
Benthopelagic–planktivorous	0.4	1.0	1.1	0.8	0.2	0.1	36.7	12.3
Pelagic–planktivorous	0.8	6.6	3.0	3.5	0.0	0.0	6.3	2.1

For fish guilds, total catches were similar on shallow and deep tracks (averages of 199 kg and 164 kg per track respectively in Table 5.03). The benthic-dwelling invertebrate feeders guild was more abundant on shallow tracks (59.7 kg compared with 11.6 kg). Benthopelagic planktivores were very abundant on one deep track (19) but otherwise scarce. On both sets of tracks the dominant fish guild was the benthopelagic invertebrate feeders (60 and 75 percent of the average catch in each group). The second largest component of catch was benthic invertebrate feeders (30 and 8 percent of the average catch in each group). It is noteworthy that no pelagic piscivores were caught.

In summary, the following groups were caught in much larger quantities on shallow tracks: algae, ascidians, bivalves, holothurians, zoantharians, mobile benthic species as a whole, and benthic invertebrate-feeding fish. Apart from a large catch of benthopelagic planktivores on one deep track (19), the remaining benthic classes and fish guilds were more or less equally abundant on deep and shallow tracks.

5.3.3 Statistical analysis of biomass depletion

The results of repeated trawling on each track can be visually assessed from graphs of the catch for each trawl plotted against the previous cumulative catch. On each graph, the least squares regression line is also displayed. The first set of graphs (Figures 5.16 to 5.21) shows the results for the sessile benthic classes for all tracks; the second set (Figures 5.22 to 5.27) the results for the mobile benthic classes; and the last set (Figures 5.28 to 5.33) shows the results for the fish guilds.

A few classes or guilds closely fit the Leslie–Davis depletion model: for example zoantharians and ascidians on track 4 (Figure 5.16), bryozoans on track 19 (Figure 5.20), and benthopelagic invertebrate feeders on track 21 (Figure 5.33). In other cases, the catch data show great variation about the fitted line. However, the slope of the line is negative for most classes or guilds (46 out of 54 graphs for sessile benthos; 57 out of 60 graphs for mobile benthos; 42 out of 54 graphs for fish guilds); this is strong evidence of depletion having taken place.

The poor fit of the Leslie–Davis model to the catch data tends to confirm the pattern seen in Figure 5.02 from 'random' simulations suggesting that the depletion rate does vary between trawls. For the first couple of shots each day, the gear may have fished harder due to ropes drying out overnight and chains rusting on deck. Trawls were conducted in both directions along each track and the prevailing currents and tides would have had an influence on gear efficiency. Sessile benthos could have been loosened in early trawls and picked up later. Mobile benthos and fish could have been scattered and then aggregated after a pause in trawling between the first and second sets.

Estimates of the mean percent depletion rate per trawl, q, are presented in Table 5.04 for sessile benthos, Table 5.06 for mobile benthos and Table 5.08 for fish guilds. The estimated percentage of the original biomass removed after 13 trawls, together with total catch, are presented in Table 5.05 for sessile benthos, Table 5.07 for mobile benthos and Table 5.09 for fish guilds.

Table 5.04 Estimated percent depletion rate for sessile benthic classes on each track, with average for all classes.

Class	Shallow Tracks						Deep Tracks						Average for all tracks	
	4		18		21		12		15		19			
	q	SE	*q*	SE	*q*	SE	*q*	SE	*q*	SE	*q*	SE	*q*	SE
All sessile	10.6	*3.3*	3.1	*4.8*	1.6	*5.0*	3.3	*3.4*	12.3	*4.2*	9.7	*3.4*	6.8	*1.7*
Algae	2.9	*7.3*	5.4	*4.5*	−10.8	*5.2*	−2.9	*3.8*	24.8	*10.8*	9.5	*21.6*	4.8	*4.4*
Porifera	7.4	*5.9*	8.8	*6.8*	4.4	*7.2*	3.4	*3.8*	12.5	*4.9*	9.9	*3.5*	7.7	*2.2*
Hydrozoa	7.9	*5.8*	7.1	*5.0*	−15.4	*4.1*	7.3	*4.6*	22.6	*10.2*	−0.4	*5.3*	4.9	*2.5*
Gorgoniacea	69.4	*5.2*	9.9	*5.3*	9.5	*6.8*	24.8	*10.7*	18.4	*6.7*	12.1	*4.3*	24.0	*2.8*
Alcyonacea	15.6	*6.3*	21.1	*7.4*	−5.6	*5.9*	7.6	*4.4*	14.4	*4.4*	10.2	*4.9*	10.6	*2.3*
Zoantharia	26.5	*2.7*	−23.3	*8.4*	7.5	*6.1*	−2.3	*7.5*	17.8	*4.7*	5.7	*5.3*	5.3	*2.5*
Bryozoa	8.6	*5.1*	7.0	*6.9*	−12.9	*5.6*	7.0	*4.4*	10.4	*3.0*	16.2	*3.6*	6.1	*2.0*
Ascidiacea	13.1	*3.1*	13.9	*6.1*	11.4	*5.6*	3.5	*5.9*	9.2	*4.2*	5.3	*6.2*	9.4	*2.2*

Table 5.05 Total catch (kg) of sessile benthic classes in 13 trawls on each track, and estimate of proportion of original biomass removed.

Class	Shallow Tracks						Deep Tracks					
	4		18		21		12		15		19	
	Catch	%	Catch	%	Catch	%	Catch	%	Catch	%	Catch	%
All sessile	*679.0*	76	*587.0*	33	*441.0*	19	*314.0*	36	*129.0*	81	*540.0*	73
Algae	*43.3*	33	*165.9*	51	*103.9*	–	*12.3*	–	*8.6*	100	*0.9*	82
Porifera	*236.7*	63	*126.0*	71	*211.0*	45	*250.0*	36	*73.4*	81	*479.8*	74
Hydrozoa	*0.7*	66	*1.2*	62	*2.2*	–	*1.5*	63	*2.6*	100	*0.3*	–
Gorgoniacea	*5.5*	100	*6.5*	75	*5.8*	75	*3.8*	100	*3.5*	94	*12.4*	82
Alcyonacea	*3.8*	93	*38.8*	100	*3.0*	–	*13.6*	65	*6.7*	89	*6.3*	78
Zoantharia	*46.1*	98	*154.6*	–	*67.1*	63	*3.1*	–	*2.1*	94	*0.7*	54
Bryozoa	*2.1*	70	*7.1*	61	*4.6*	–	*17.5*	62	*5.4*	77	*15.0*	91
Ascidiacea	*340.5*	83	*86.8*	86	*42.9*	79	*12.1*	37	*26.8*	71	*24.5*	51

Table 5.06 Estimated percent depletion rate for mobile benthic classes on each track, with average for all classes.

Class	Shallow Tracks						Deep Tracks						Average for all tracks	
	4		18		21		12		15		19			
	q	SE	*q*	SE	*q*	SE	*q*	SE	*q*	SE	*q*	SE	*q*	SE
All mobile	4.9	*2.6*	13.2	*6.1*	2.4	*3.4*	3.9	*3.6*	14.5	*4.8*	13.9	*4.6*	8.8	*1.8*
Crustacea	15.0	*5.0*	10.3	*4.4*	4.0	*3.4*	18.5	*5.8*	16.9	*4.5*	16.4	*6.4*	9.6	*2.0*
Bivalvia	4.9	*4.3*	8.3	*7.1*	–2.9	*3.8*	15.5	*6.9*	25.4	*5.5*	12.0	*7.6*	10.5	*3.6*
Gastropoda	49.2	*7.7*	12.0	*10.5*	29.5	*4.6*	20.0	*7.8*	15.5	*12.2*	21.5	*7.6*	24.6	*3.6*
Cephalopoda	17.2	*5.4*	2.2	*8.3*	6.0	*11.5*	10.9	*8.2*	–0.9	*7.4*	8.6	*6.5*	7.3	*3.3*
Asteroidea	9.8	*5.0*	26.1	*8.2*	4.0	*3.6*	1.5	*8.3*	7.9	*7.1*	18.6	*10.0*	11.3	*3.0*
Crinoidea	13.8	*9.0*	13.2	*6.4*	3.1	*3.5*	1.6	*2.8*	9.6	*4.1*	7.0	*4.8*	8.1	*2.2*
Echinoidea	15.0	*5.1*	3.6	*6.9*	6.9	*8.2*	7.9	*6.8*	13.0	*7.9*	16.6	*16.4*	10.5	*3.8*
Holothurordea	3.8	*2.1*	20.5	*7.1*	1.8	*3.5*	–3.6	*3.7*	28.9	*11.5*	12.4	*5.0*	10.6	*2.6*
Ophiuroidea	–1.2	*4.2*	9.9	*7.0*	14.9	*9.4*	7.8	*7.4*	8.3	*4.8*	30.8	*16.8*	11.8	*3.8*

Table 5.07 Total catch (kg) of mobile benthic classes in 13 trawls on each track, and estimate of proportion of original biomass removed.

Class	Shallow Tracks						Deep Tracks					
	4		18		21		12		15		19	
	Catch	%	Catch	%	Catch	%	Catch	%	Catch	%	Catch	%
All mobile	*977.0*	48	*842.0*	86	*361.0*	27	*64.0*	40	*69.0*	88	*40.0*	88
Crustacea	*9.9*	89	*4.5*	75	*4.2*	41	*5.5*	98	*6.8*	91	*9.9*	93
Bivalvia	*237.9*	48	*326.6*	68	*15.2*	–	*0.4*	100	*11.9*	100	*0.4*	79
Gastropoda	*9.6*	100	*17.6*	86	*3.6*	100	*10.7*	96	*10.2*	92	*3.9*	100
Cephalopoda	*0.5*	89	*2.0*	25	*2.4*	58	*2.5*	80	*1.9*	–	*1.4*	70
Asteroidea	*42.6*	74	*27.6*	100	*81.9*	41	*12.0*	18	*12.0*	67	*15.1*	100
Crinoidea	*45.5*	90	*17.7*	86	*7.8*	34	*4.9*	19	*6.0*	74	*1.6*	61
Echinoidea	*5.3*	87	*1.5*	38	*4.4*	62	*4.1*	67	*2.1*	81	*2.0*	100
Holothurordea	*621.6*	40	*444.1*	100	*240.4*	21	*21.1*	–	*16.6*	100	*4.9*	82
Ophiuroidea	*4.3*	–	*0.6*	74	*1.4*	92	*2.5*	67	*1.3*	69	*1.2*	100

Table 5.08 Estimated percent depletion rate for fish guilds on each track, with average for all classes, in descending order of depletion rate.

Class	Shallow Tracks						Deep Tracks						Average for all tracks	
	4		18		21		12		15		19			
	q	SE	*q*	SE	*q*	SE	*q*	SE	*q*	SE	*q*	SE	*q*	SE
All fish	13.1	*7.8*	4.6	*4.5*	47.8	*5.4*	5.2	*2.6*	–0.8	*2.5*	–7.8	*4.2*	10.4	*2.0*
Benthopelagic–herbivorous	49.7	*16.3*	9.8	*6.3*	43.9	*13.9*	23.6	*11.0*	25.6	*9.4*	28.0	*13.0*	30.1	*4.9*
Benthic–invertebrate	12.2	*15.2*	10.8	*9.6*	74.3	*7.0*	5.7	*3.6*	6.2	*5.2*	10.1	*3.6*	19.9	*3.4*
Benthopelagic–mixed	33.1	*10.7*	11.9	*6.8*	44.7	*5.0*	5.8	*3.1*	3.2	*4.9*	16.2	*8.0*	18.1	*2.8*
Benthic–piscivorous	15.8	*7.1*	2.6	*4.7*	5.3	*6.1*	9.5	*4.8*	6.2	*4.7*	12.7	*3.3*	8.6	*2.2*
Benthopelagic–invertebrate	18.9	*4.8*	4.1	*4.6*	19.4	*2.7*	5.1	*2.6*	–1.2	*2.3*	–09.7	*2.9*	6.1	*1.4*
Benthic–mixed	27.3	*11.2*	6.3	*12.9*	4.7	*8.9*	–51.1	*41.1*	7.2	*10.7*	22.5	*10.6*	2.8	*8.0*
Benthopelagic–planktivorous	31.7	*7.2*	–5.0	*10.5*	1.4	*10.7*	21.6	*10.3*	–70.4	*35.0*	–46.8	*18.7*	–10.5	*7.4*
Pelagic–planktivorous	31.5	*11.8*	8.1	*12.8*	29.8	*13.0*	–21.6	*34.4*	14.3	*15.5*	–152.1	*63.4*	–15.8	*12.8*

Table 5.09 Total catch (kg) of fish guilds in 13 trawls on each track, and estimate of proportion of original biomass removed, in descending order of depletion rate.

Class	Shallow Tracks						Deep Tracks					
	4		18		21		12		15		19	
	Catch	%	Catch	%	Catch	%	Catch	%	Catch	%	Catch	%
All fish	*209.0*	86	*203.0*	48	*184.0*	100	*67.0*	50	*92.0*	–	*332.0*	–
Benthopelagic–herbivorous	*11.1*	100	*1.8*	77	*0.3*	100	*0.1*	95	*0.1*	100	*6.9*	100
Benthic–intvertebrate	*68.8*	94	*6.5*	84	*103.8*	100	*2.8*	53	*9.0*	57	*23.1*	76
Benthopelagic–mixed	*7.1*	100	*25.5*	85	*3.0*	100	*4.0*	54	*9.1*	–	*26.0*	95
Benthic–piscivorous	*2.1*	92	*1.5*	31	*1.2*	51	*1.7*	74	*1.7*	57	*2.8*	82
Benthopelagic–invertebrate	*117.7*	97	*159.4*	44	*67.7*	94	*57.9*	50	*71.9*	–	*226.6*	–
Benthic–mixed	*0.3*	97	*0.8*	67	*0.0*	47	*0.0*	100	*0.0*	65	*1.0*	95
Benthopelagic–planktivorous	*0.4*	100	*1.0*	–	*1.1*	17	*0.2*	100	*0.0*	100	*36.7*	100
Pelagic–planktivorous	*0.8*	100	*6.6*	77	*3.0*	100	*0.0*	–	*0.0*	100	*6.3*	100

The depletion rate has been estimated from the decline in catch with repeated trawling. Earlier we showed that this can under-estimate removal rates when repeated trawls do not cover exactly the same ground. It is also possible to over-estimate the true removal rate for some classes of benthos since there are certain to be organisms that the trawl has a negligible chance of catching, because of the height of the footrope, the physical characteristics of the organism and the nature of the terrain. Video footage from a camera attached to the net during the repeated trawling experiment has shown that many small or flexible organisms such as seawhips and gorgonians are not caught by the net and many remained after 13 trawls even though the regression analysis indicated that they were heavily depleted. It is, however, difficult to identify and assess the biomass of organisms not caught by the prawn trawl because of the poor resolution of video when mounted on the trawl net.

In some instances the catch increased as more trawls were carried out, resulting in a negative estimate for the depletion rate. For sessile benthos these negative estimates have been interpreted as an imprecise estimate of a (positive) removal rate, since it is not possible for a sessile population to increase in the interval between trawls. Another possibility was that earlier trawls loosened sessile benthos that was picked up by later trawls. For mobile benthos, there is a possibility that organisms moved into the trawled area, but this is considered unlikely because most estimates were positive and the negative depletion estimates were quite close to zero – consistent with the behaviour of estimates when the underlying "true" value is small and positive. For fish guilds, there were some large negative estimates of q, suggesting that fish could be moving into the trawled area. However, there was no guild for which all tracks had a negative estimate of q, so the correct interpretation of these estimates is unclear.

For sessile benthos (Table 5.04), the average depletion rate per trawl across all tracks ranged from 4.8 percent for algae to 24.0 percent for gorgonians; the average for all sessile benthos was 6.8 percent. However, the estimate for gorgonians (including sea whips) was dominated by the results of plot 4, where about 3.5 kg were caught in the first trawl, but then less than 0.5 kg thereafter. Subsequent video evidence showed many gorgonians (more than had been caught) remained in situ, although most showed evidence of damage. The flexible skeletons of gorgonians and seawhips make them resilient to removal. We suggest individuals were removed quickly but then catchability (q) decreased substantially. On shallow tracks, the depletion rate for ascidians was twice as large as on deep tracks. Ascidians were nearly ten times more abundant on shallow tracks than on deep tracks, so this may have influenced the depletion rate. For other organisms that were more abundant on shallow tracks, the depletion rates were similar (though variable) across both sets of tracks.

The estimated proportion of sessile benthos removed after 13 trawls is shown in Table 5.05. There is considerable variation between tracks and across classes. In some cases no estimate could be obtained because the catch did not decrease with repeated trawls. Classes that appeared to have been severely depleted were: gorgonians (75–100 percent), alcyonarians (65–100 percent), ascidians on shallow tracks (79–86 percent). Note, however, the caution above regarding gorgonians — many remained on the tracks after the experiment and the BACI dredge data suggested that at least 40–60 kg would have been present initially on each tack, compared with the totals of 3.5–12.5 kg removed. A large proportion of sponges (Porifera) appeared to have been removed (36–81 percent). Altogether, between 33 and 81 percent of the total sessile benthos appears to have been removed.

For mobile benthos (Table 5.06), the average depletion rate per trawl across all tracks ranged from 7.3 percent for cephalopods to 24.6 percent for gastropods; the average for all mobile benthos was 8.8 percent. On shallow tracks, the depletion rate for bivalves and crustaceans was lower than on deep tracks. For other classes the depletion rate was similar across both sets of tracks.

The estimated proportion of mobile benthos removed after 13 trawls is shown in Table 5.07. Gastropods appeared to have been severely depleted (86–100 percent). The impact on holothurians was highly variable, ranging from 21 to 100 percent even on shallow tracks where large quantities were caught (240–620 kg). Altogether, between 27 and 80 percent of total mobile benthos appears to have been removed. For most classes on all tracks, at least half of the original biomass appeared to have been removed.

The depletion rates for fish guilds are shown in Table 5.08. The average depletion rate per trawl across all tracks ranged from –15.8 percent for pelagic planktivores (fish apparently moving into the trawled area) to 30.1 percent for benthopelagic herbivores; the average for all fish was 10.4 percent. Only three guilds were consistently caught in substantial quantities: benthic invertebrate-feeders, benthopelagic mixed-feeders and benthopelagic invertebrate-feeders. For these guilds, depletion rates were higher on shallow tracks (32.4, 29.9 and 14.1 percent respectively) even where the total catch was similar across the two sets of tracks.

On track 19, three guilds apparently increased in abundance with repeated trawling. These were: benthopelagic invertebrate-feeders, benthopelagic planktivores and pelagic planktivores. The species composition of each guild on the different tracks was examined with a view to isolating the reasons for the different response to trawling observed on track 19.

Among the benthopelagic invertebrate-feeders, three species (*Nemipterus furcosus*, *Pentapodus paradiseus* and *Choerodon cephalotes*) were noticeably more abundant on track 19 than on other tracks, while one species (*Pristotis jerdoni*) was much less abundant. *N. furcosus*, for example, was found in every trawl on track 19 but in only one or two trawls on the other tracks and was caught in much larger quantities (4.5 kg on average compared with 0.1 kg on other tracks). Only 0.6 kg of *P. jerdoni* was caught in all trawls on track 19 compared with an average of about 18 kg on the other tracks. These differences in species abundance can be explained by the fact that track 19 has relatively fine sediment (as opposed to rubble and/or coarse sediments), a habitat preferred by species such as *N. furcosus,* which is commonly found in trawl grounds. This substrate would have less of the structured habitat favoured by such species as *P. jerdoni*. Furthermore, the response of *N. furcosus* and *P. paradiseus* to trawling on track 19 (Figure 5.34) was an unambiguous increase in catch over time on each of the two days of trawling. This response strongly suggests that these species were attracted in to feed on the debris from trawling.

For the benthopelagic planktivores, the overwhelming reason for the difference between track 19 and the rest was the high abundance of one species: *Selaroides leptolepis* (total of 32.2 kg compared with an average of 0.2 kg on the others). This schooling species is known to be more abundant on muddy substrates. The catch showed no particular pattern on the first day of trawling, then showed a fairly steady increase during the second day of trawling, ending with a catch of 16 kg. This general pattern was also followed by *Selar boops*, a pelagic planktivore in the same family as *S. leptolepis*.

5.4 Discussion

If a single trawl had a massive impact on seabed fauna, there would be little need for repeat trawl experiments since one or two passes of a trawl will remove nearly the entire fauna. There was some prior evidence suggesting that trawl impacts were very large. Sainsbury et al (1992) used a video camera to assess the amount of damage caused to sponges by a fish trawl on the North West Shelf of Australia. Because many sponges passed under the net, they were unsure of the fate of half of the sponges passing under the trawl. However, where the fate of the impact was known (188 cases), only 10% of sponges remained attached, the remaining 90% were detached from the seabed. If such a large impact were to occur across the entire fauna, then trawls would rapidly deplete it. However, we have shown in the BACI experiment (Chapter 4) that the overall impact for prawn trawls is around 10%. Certainly some groups, especially tall sponges, are more vulnerable, but there is a large proportion of the epibenthos that is more resistant. Because of this differential vulnerability, the real effect of multiple trawls can be expected to be complex. Repeat trawling experiments simulate what happens in commercial trawling and so are an obvious way of studying the impacts of trawling. Few repeat trawl or dredge experiments have been carried out, because of the cost, the difficulty of finding unfished areas and the technical difficulties associated with the repeated trawling. One of the few comparable repeat trawl experiments is that described by Gordon et al. (1997). This involved trawling three 13 km long corridors 12 times with an Engel otter trawl each year for three years and should provide information on longer term effects. A major difficulty of repeat trawl or dredge experiments relates to the problem of towing the gear repeatedly over the same area. Because of wind, sea and current, the ships heading has to be continually adjusted in order to remain on track and the gear which may be a hundred or more metres behind the ship does not necessarily follow the track of the ship. It is possible to monitor the position of the ship and the gear very accurately using a combination of differential Global Position System and sonar acoustic tracking (McKeown and Gordon 1997), but this does not guarantee a uniform impact on the seabed. The wider the gear, the wider the path of the impact and this can assist in achieving a more uniform impact coverage. The depth of water also affects the accuracy of the track, since a longer tow line has to be used in deeper water and this makes for a greater error in positioning of the gear.

In our experiment, the experimental impact of a 12 fathom (22 metre) prawn net towed 13 times along the one track was not uniform because the track followed by the trawl varied. The general pattern was for a central track between 11 m and 14 m wide that was trawled at least 10 times, and a track between 17 m and 19 m wide that was trawled at least 6 times. Even though the trawling was done very accurately, the intensity of depletion varied from low at the edge of the swathe to high in the centre. For example, if the actual depletion rate was 20 percent per trawl, then the depletion would have ranged from 20 percent at the edges to 95 percent near the centre, which was trawled 13 times. Consequently, the statistical estimates of depletion rate underestimated the actual rate. To determine how much the estimated depletion rates should be inflated to provide an estimate of the actual depletion rate per trawl, analysis of simulated trawl catch sequences (with varying catch efficiency and varying trawl position) was carried out. The results of this suggested that the values presented in this report should be inflated by at least 25 percent.

We collected more material from the shallow (~20 m) tracks than the deep (~35 m) - a mean of 569 kg of sessile animals per shallow versus 328 kg per deep track. More mobile invertebrates were taken in the shallow plots (727 kg) than from the deep plots (58 kg). Fish showed the opposite trend with a mean of 199 kg from shallow tracks versus 164 kg for deep tracks. Sponges dominated the sessile benthos from the deep plots (82 percent of catch). Sponges and soft corals (alcyonarians) made up 61 percent of the shallow sessile benthos. The large catch of sessile invertebrates indicates that the inter-shoal and inter-reef area of the GBR is likely to be highly susceptible to trawling. Collie et al (1996) point out that habitats with three-dimensional structure tend to be more sensitive to fishing disturbance than communities with mobile sandy sediments and little three-dimensional structure

The Leslie-Davis depletion coefficient analysis confirms that an overall depletion is taking place with successive trawls. The slope of the lines fitted to the data was negative for 46 out of 54 cases of sessile benthos, for 57 out of 60 cases for mobile benthos and for 42 out of 54 cases for fish guilds. However, within these cases there was considerable variation. We suggest two causes for this. The first is that since the trawl did not follow exactly the same track, it is likely that a later trawl in a series might have encountered a patch that was both rich and unfished giving a high catch value for that track. The second cause could be the result of cumulative impacts. We suspect that many sessile organisms and especially gorgonians, may simply bend underneath the trawl on the first trawl impact. Successive impacts however loosen them up and eventually they are dislodged and either caught or rolled under the net. As we have pointed out in the results, other factors could be changes in gear efficiency with time of day and with direction of tow.

There are two factors independent of depletion that could affect the numbers of animals caught in successive trawls. Firstly it is possible that some mobile species move away from disturbance. For example, turbulence in the wake of trawl doors can generate large and highly turbid clouds of suspended sediment. This plume can extend about 10 m above bottom and remain for up to a day Churchill (1989). As some fish are sensitive to turbidity, it is possible that species that prefer low turbidity water may move away from freshly trawled areas. Secondly, some species may be attracted by the disturbance. In the Irish Sea for example, dab (*Limanda limanda*) species are known to aggregate in areas disturbed by trawls (Kaiser and Ramsay, 1997). The hermit crab *Pagurus bernhardus* is found in higher densities in trawl tracks than in adjacent areas (Ramsay et al. 1996). The crabs move into areas disturbed by trawls and feed on animals damaged by the trawls and on discards. Gordon et al. (1997) when conducting a repeat trawl depletion experiment found Snow crab (*Chionoecetes opilio*) numbers increased approximately 10-12 h after trawling began. We expected a similar increase from invertebrate groups known to scavenge material on the seabed especially crabs and asteroids. However, both of these groups showed clear negative trends suggesting that their populations were being depleted by successive trawls or at least that depletion rates exceeded immigration rates. We did find indications of attraction of some fish into the trawled area. Numbers of both *Pentapodus paradiseus* and *Nemipterus furcosus* increased over the course of the experiment (Figure 3.54). The increase was very large in the case of *Pentapodus paradiseus*, going on the second day from around 50 animals per trawl at the start of the second day to around 200 per trawl after 9 to 10 trawls.

The repeat trawl experiment has resulted in measurable depletion rates for seabed fauna. The mean rate for all sessile benthic classes was 7 percent but it ranged from a high of 24 percent for gorgonians to a low of 5 percent for algae. Sponges were around 8 percent and soft corals around 11 percent. The average depletion rate for mobile benthos was 9 percent but individual groups ranged from 25 percent for gastropods to 7 percent for cephalopods. Echinoderm depletion rates varied between 8 and 12 percent. The average depletion rate for fish was 10 percent. These figures are of a similar magnitude to the results of the BACI experiment (Chapter 4) even though that experiment was based on the passage of a single trawl. The depletion experiment also clearly demonstrates that even although the impact of single trawl may be relatively minor, repeated trawling results in an accumulated impact, which can be highly significant. Given the depletion underestimation factor estimated in Section 5.2.3, the depletion rates per trawl would have been 25 percent higher between 9 and 13 percent for sessile benthos, mobile benthos and most fish. The combined effect of 13 trawls would, therefore, have been removal of an estimated 70–85 percent of the apparent initial biomass of seabed communities in the centre of each trawled track. Video observations of our sites suggested that some fauna (e.g. some gorgonians and seawhips) were very resilient to removal. This appeared to conflict with the high depletion rates for these fauna. Our interpretation is that a few loose individuals were removed initially (high q), but that those remaining were much more resilient (low q), giving first high then very low catches and the impression of virtually complete depletion. Nevertheless, most of the remaining gorgonians and seawhips suffered some degree of physical damage. On the other hand, sponges are delicate and vulnerable, especially large (older) erect sponges, most of which were probably removed in the initial 1–2 trawls, while smaller sponges continued to be removed with subsequent trawls.

Trawlers fishing for prawns use a small net (try net) towed between their main nets to sample the ground over which they are trawling at around 20 minute intervals. The catch of this net is used to decide whether to continue trawling along their original track or to turn around and trawl over the ground already covered, or whether to leave the area. The trawlers use plotters linked to their GPS to maintain a record of their track. In this way they can concentrate their fishing on those grounds that yield the highest catch rates. The result of this fishing pattern is that relatively small areas are fished repeatedly over a short time period. If conducted on structured habitats, this repeat trawling will have the effects that we have described in our Repeat-trawl experiment. We would expect that in these intensively fished areas, any benthos that may have been present initially would be severely impacted. This concentration of fishing effort in areas of highest yield appears to be common to many trawl and dredge fisheries and will need to be taken into account when considering the impact of fishing.

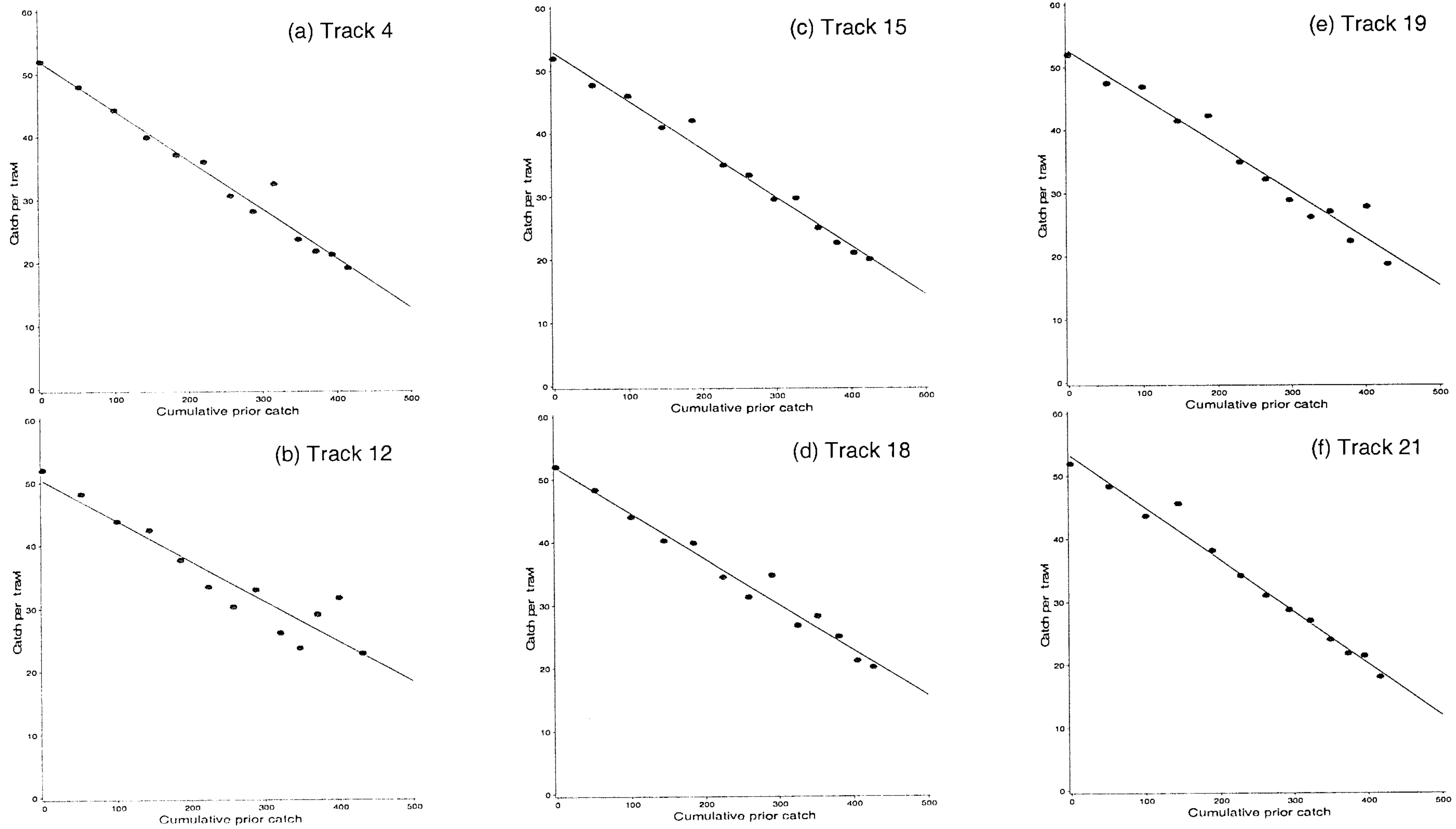


Figure 5.01 Trawl depletion data for simulations using actual trawl paths with fixed depletion of 10 percent and intial biomass of 1000 gms per grid cell.

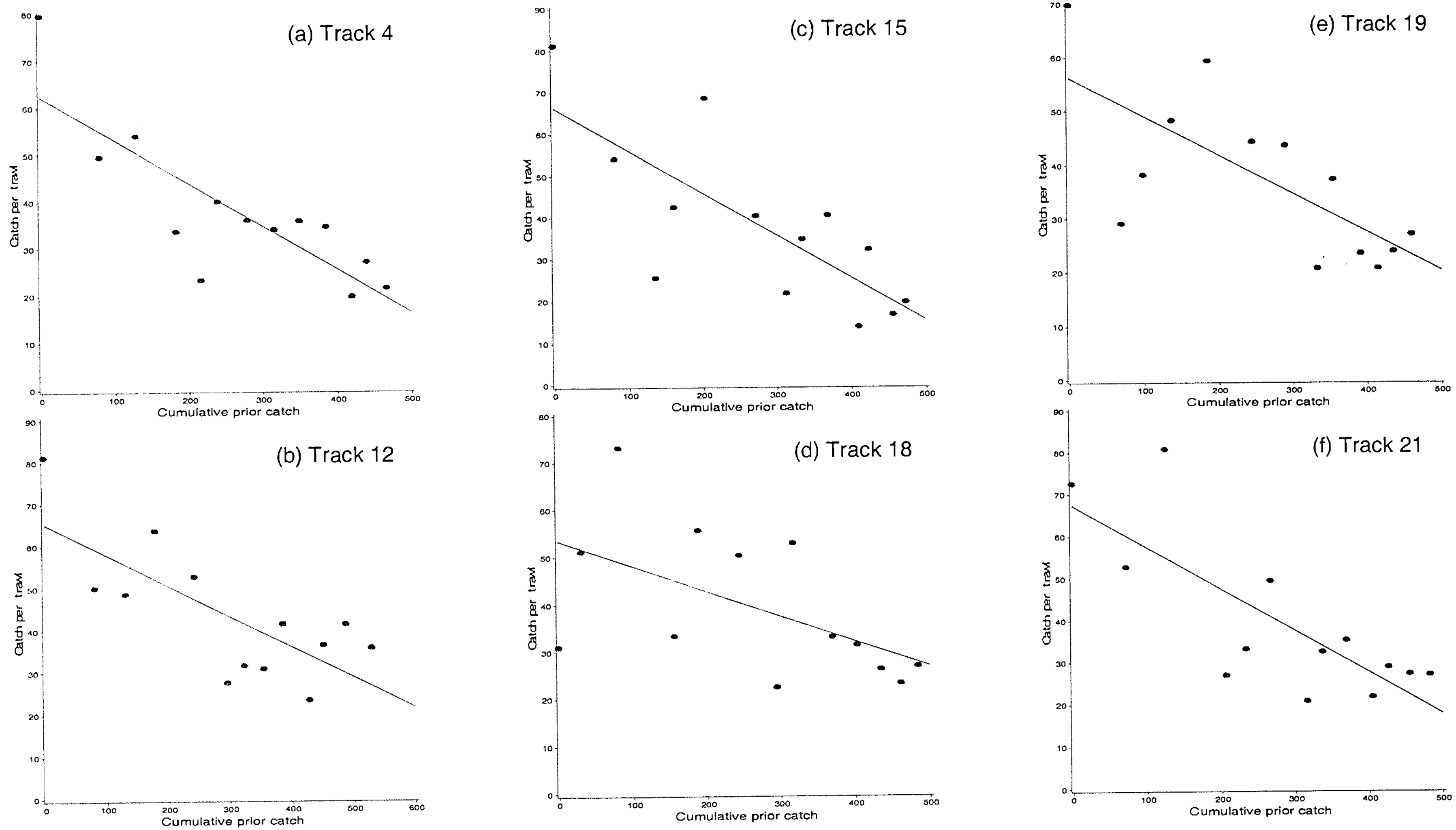


Figure 5.02 Figure 5.02 Trawl depletion data for simulations using actual trawl paths with mean random depletion of 10 percent and random intial biomass in each grid cell

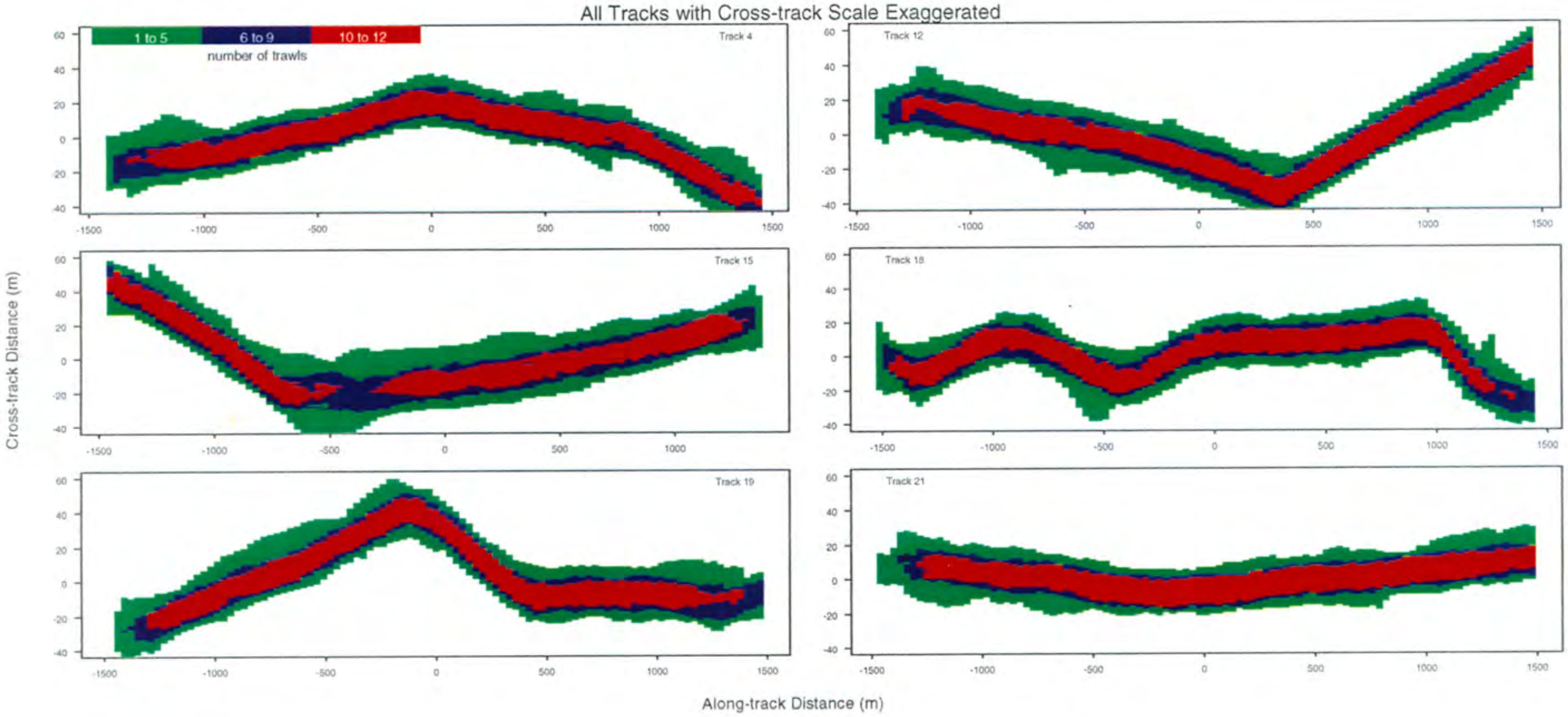


Figure 5.03 Intensity of trawling along six tracks trawled repeatedly in December 1995. Tracks appear to deviate markedly from a straight line, but this is a result of compressing the scale for the along-track distance relative to the cross-track distance.

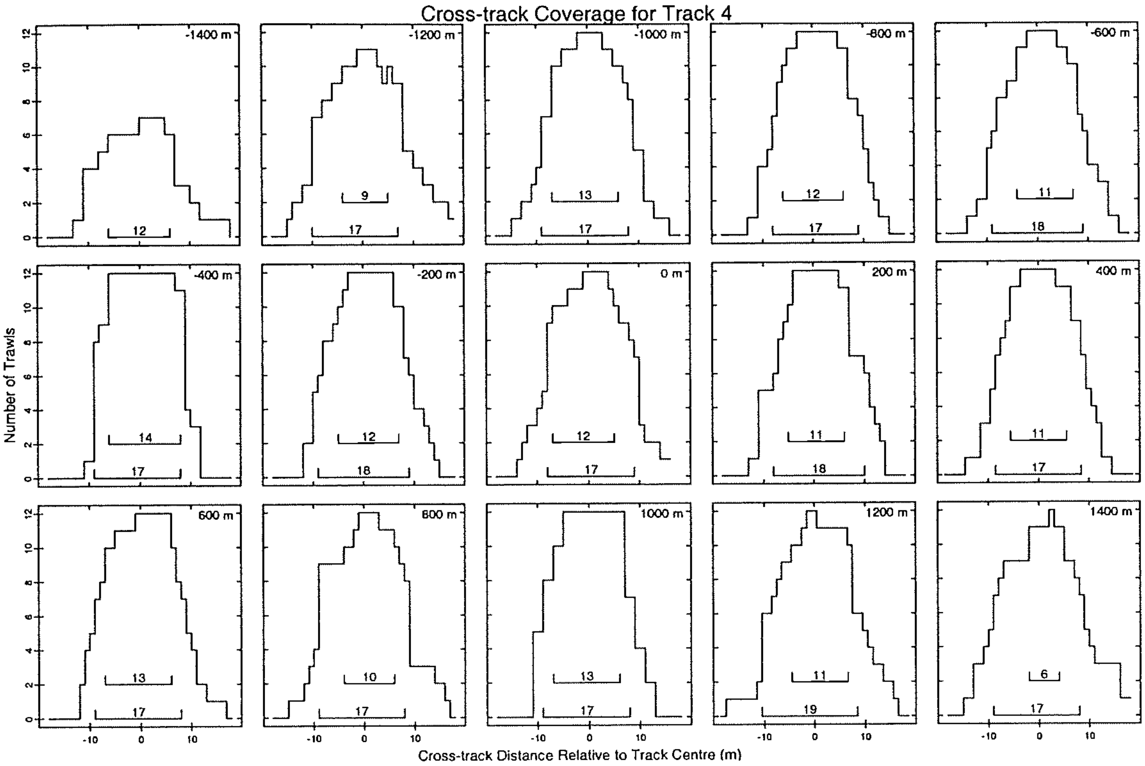


Figure 5.04 Trawl intensity profile for track 4

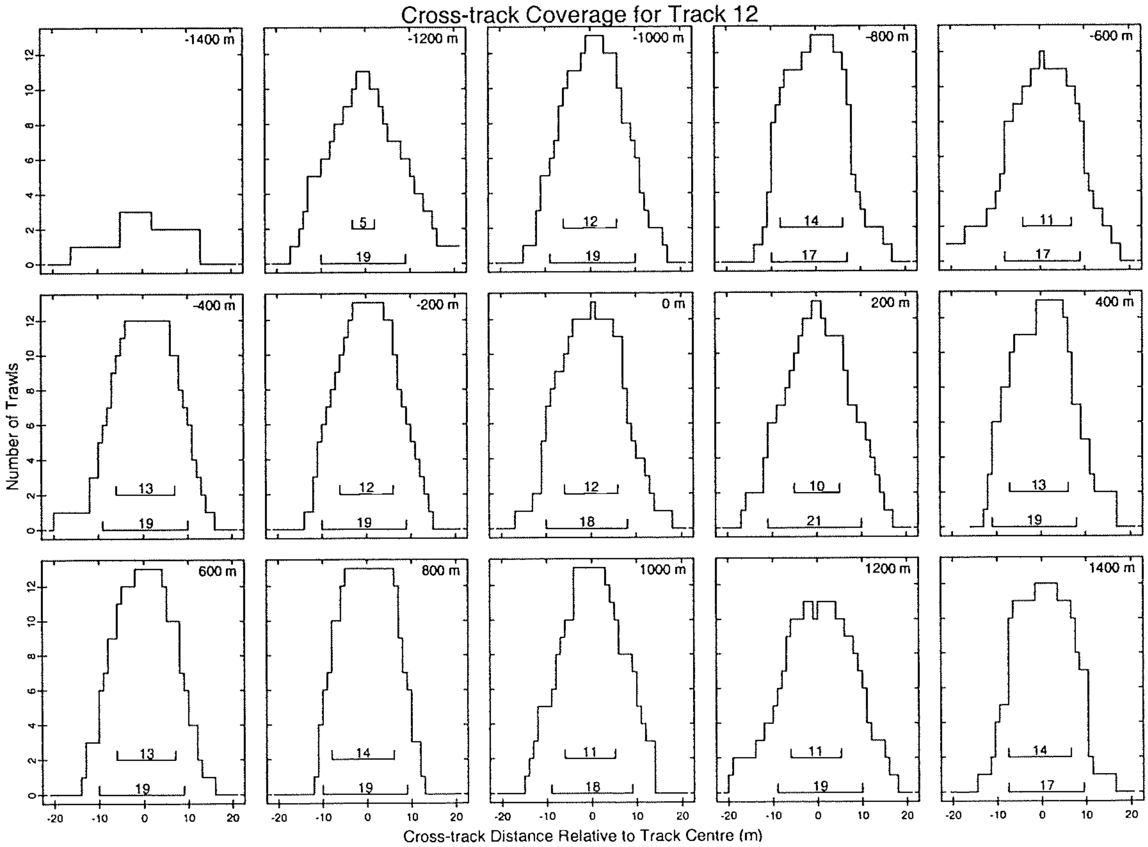


Figure 5.05 Trawl intensity profile for track 12

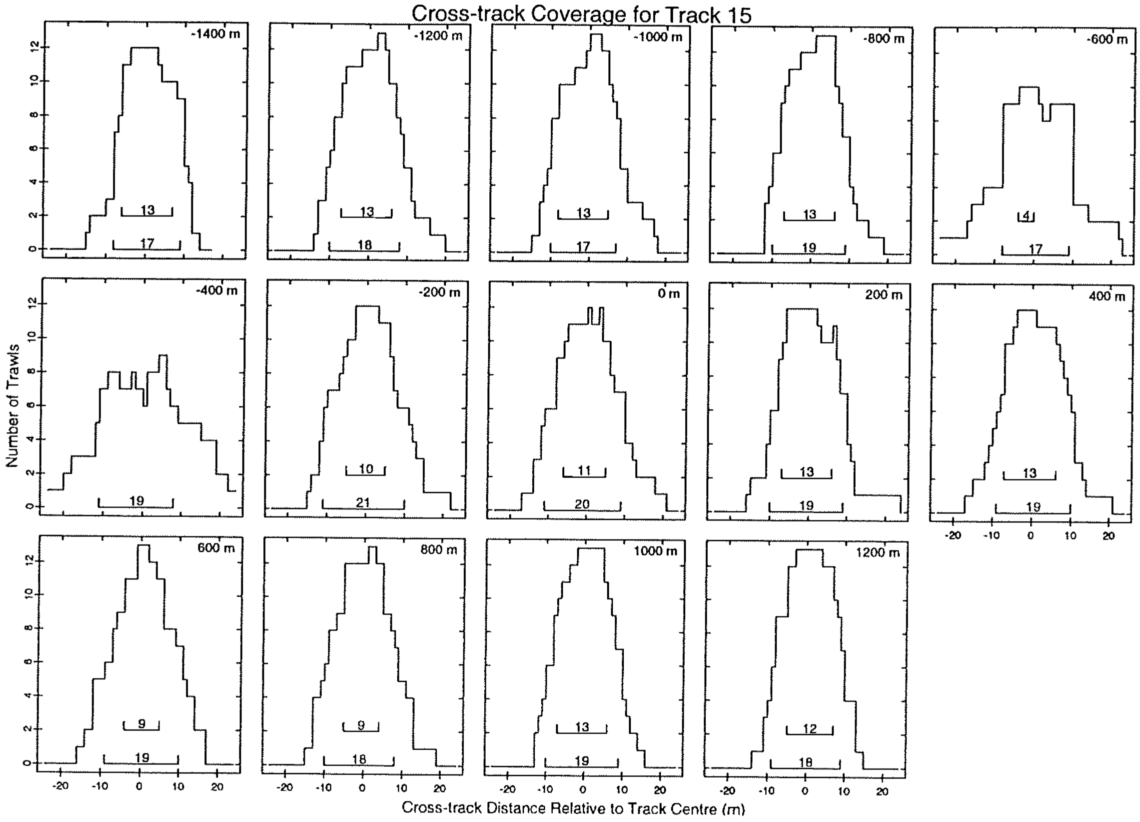


Figure 5.06 Trawl intensity profile for track 15

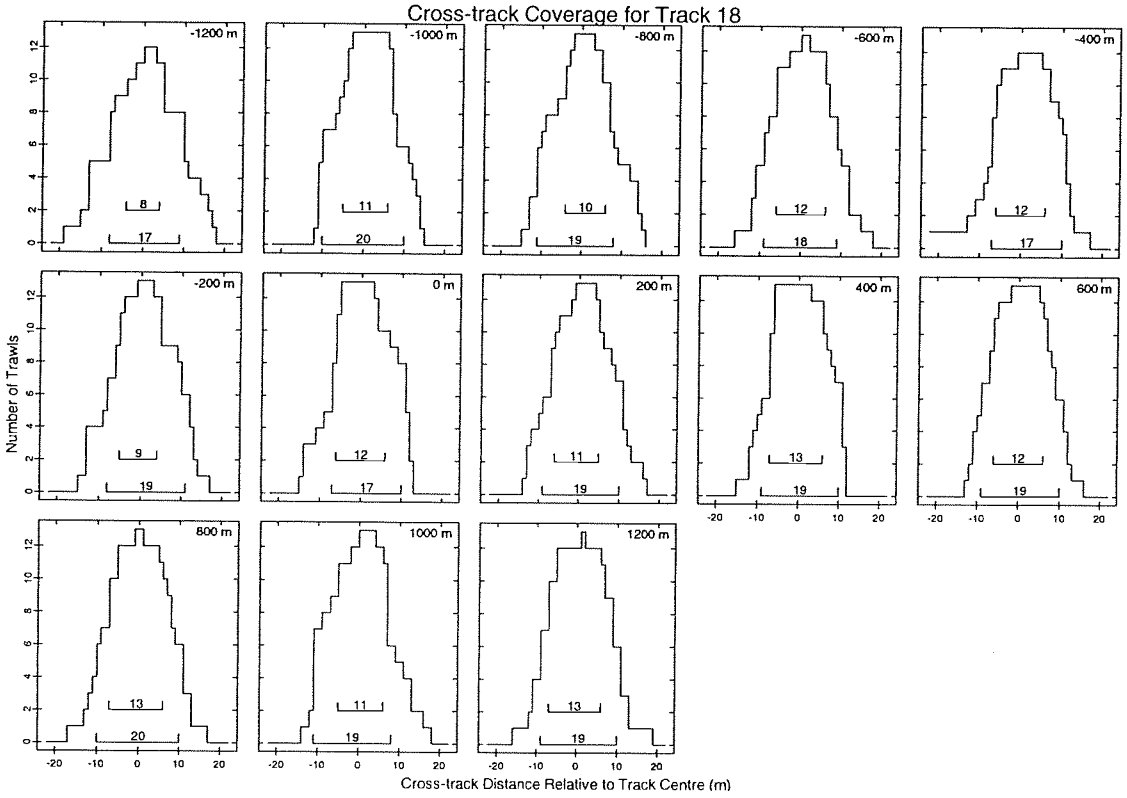


Figure 5.07 Trawl intensity profile for track 18

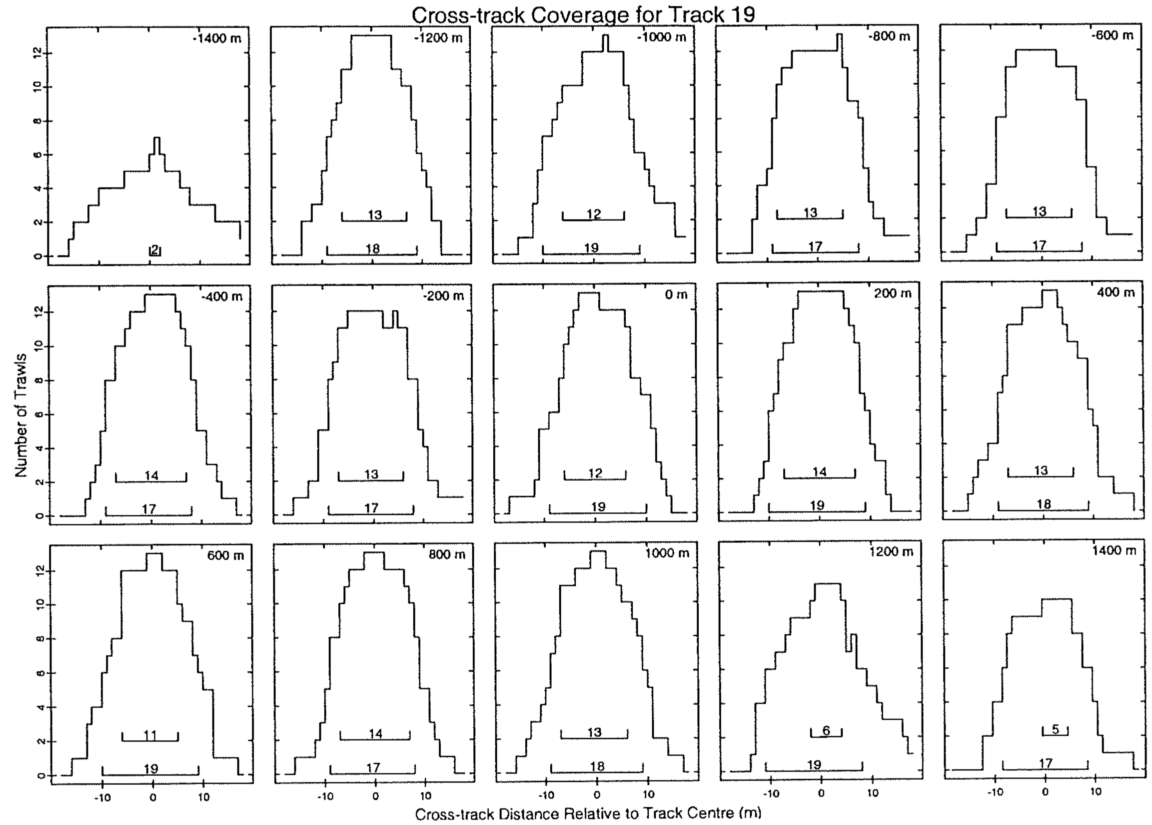


Figure 5.08 Trawl intensity profile for track 19

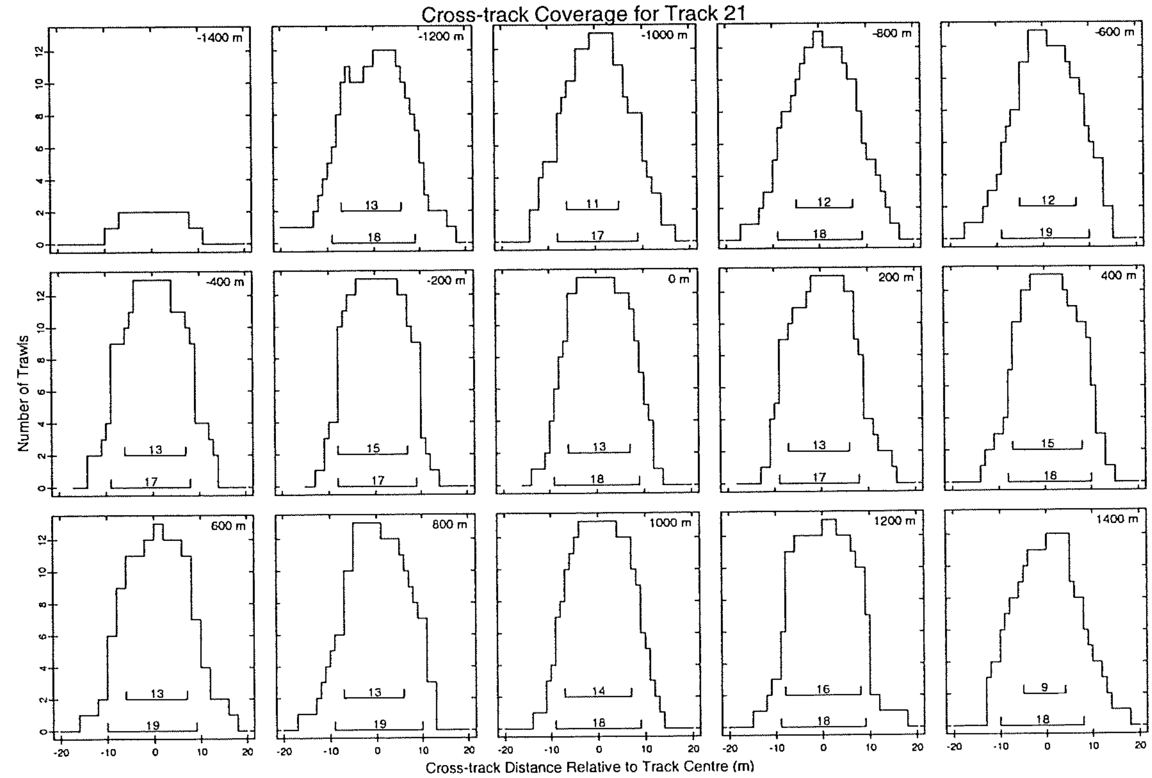


Figure 5.09 Trawl intensity profile for track 21

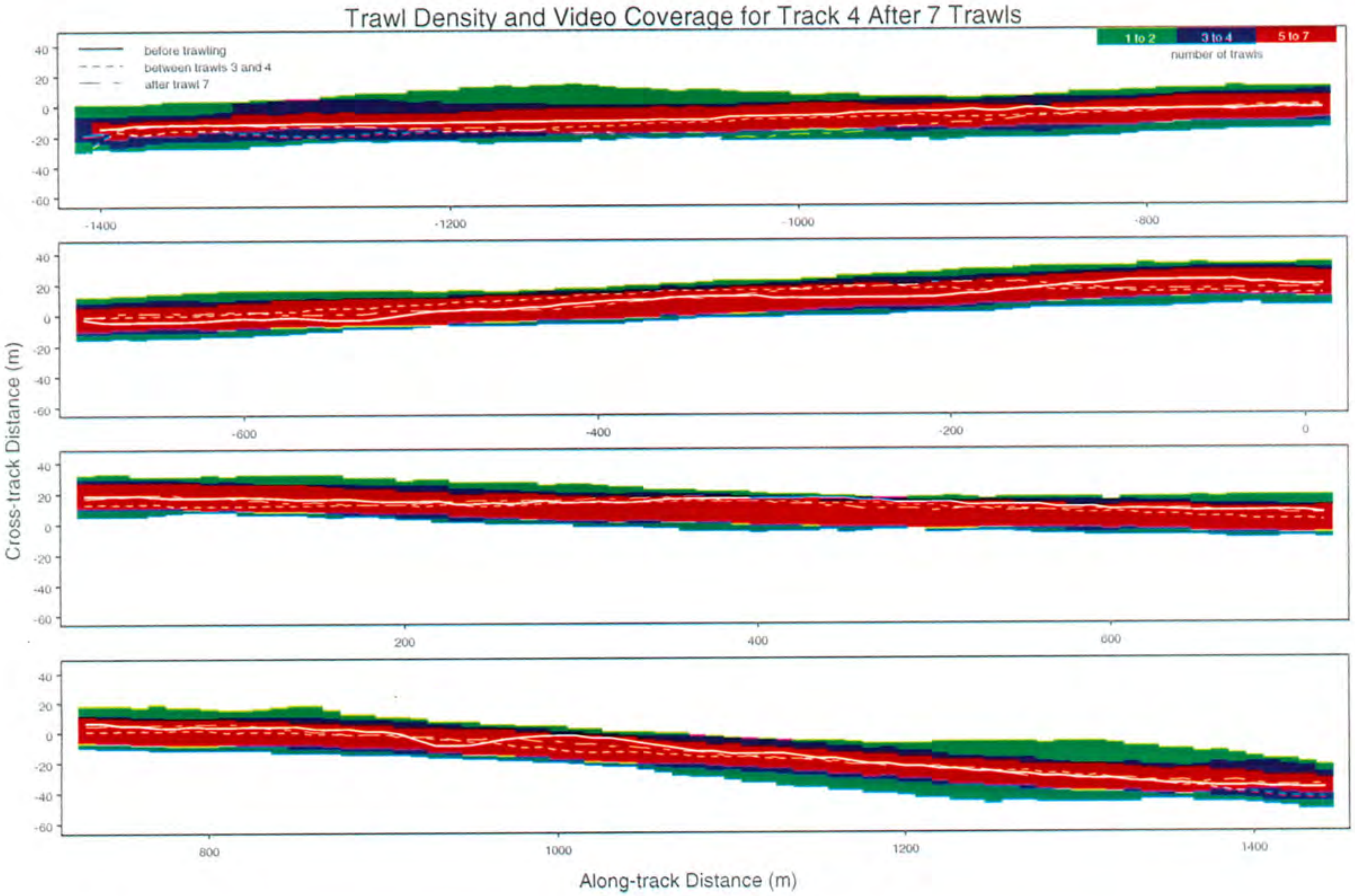


Figure 5.10 Trawl density and video coverage for track 4 after 7 trawls

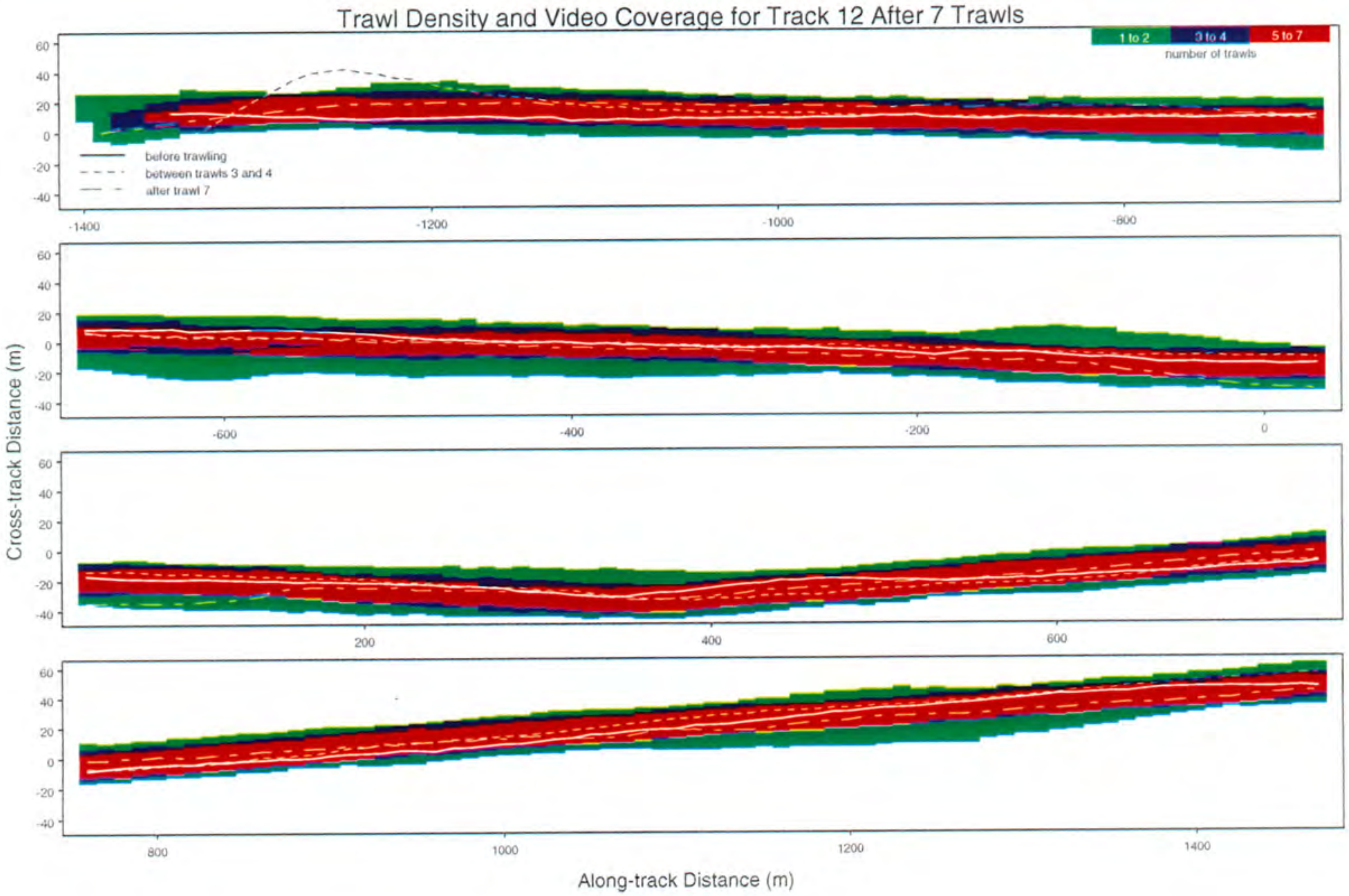


Figure 5.11 Trawl intensity and video coverage for track 12 after 7 trawls

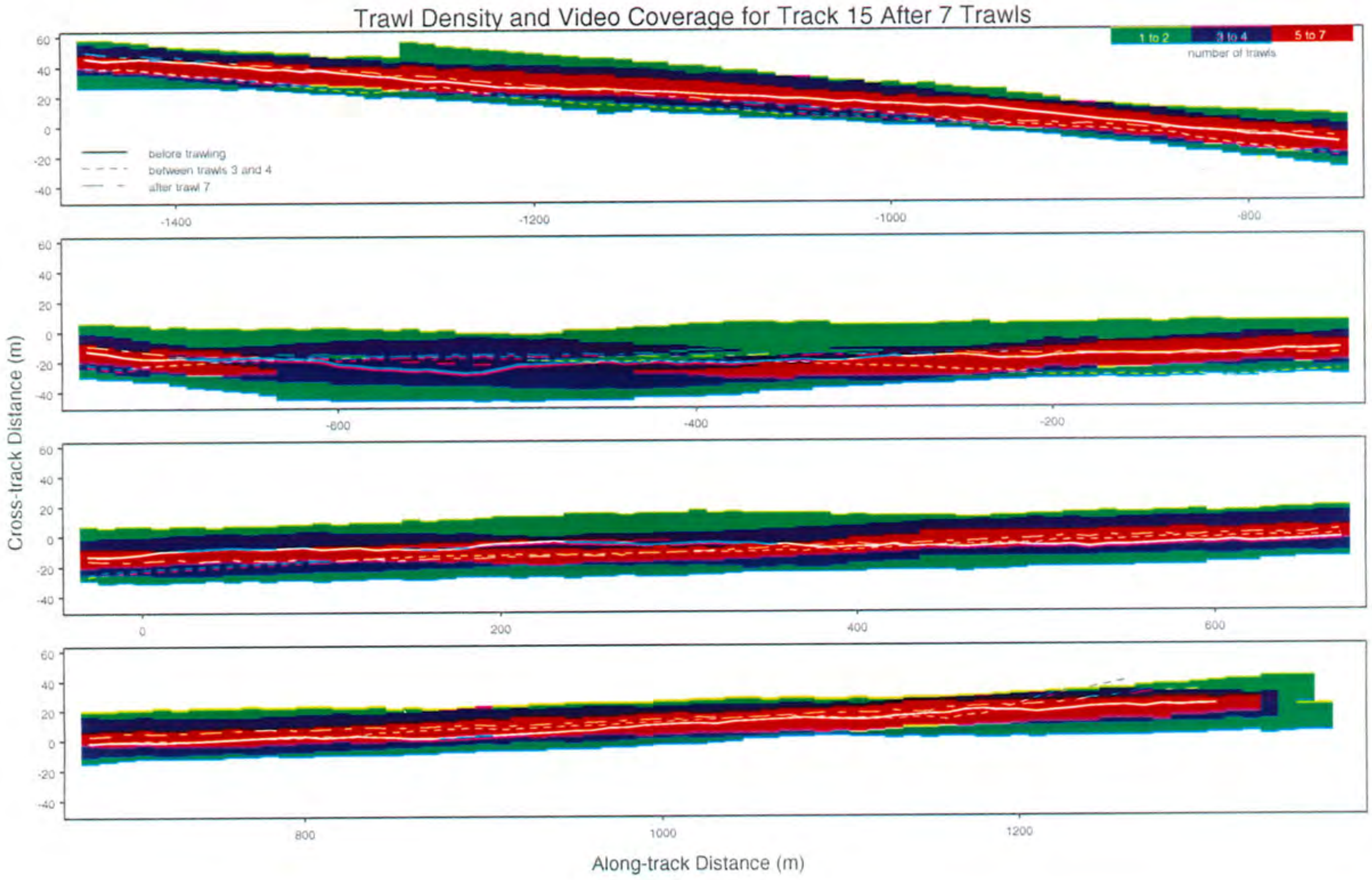


Figure 5.12 Trawl intensity and video coverage for track 15 after 7 trawls

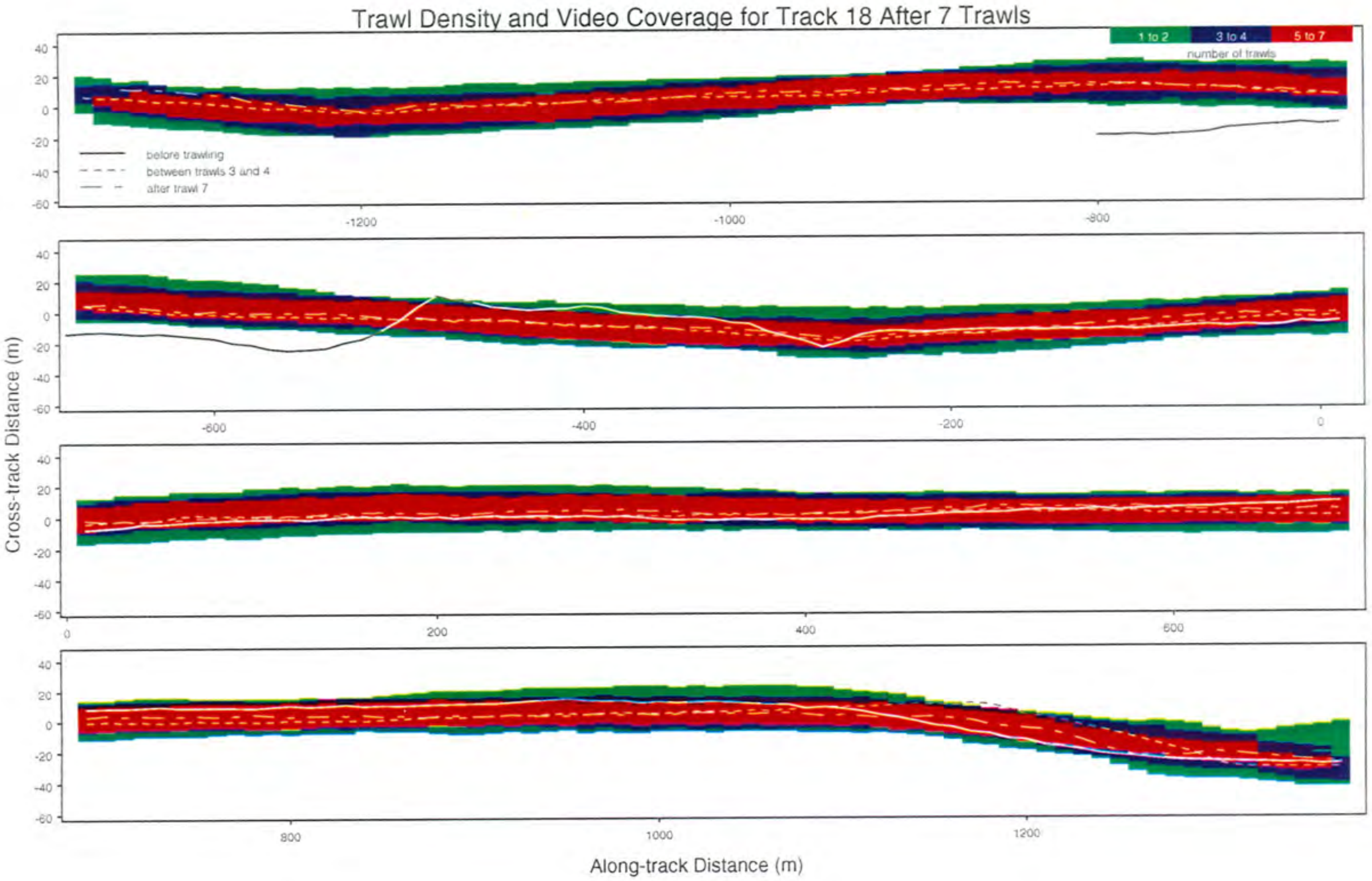


Figure 5.13 Trawl intensity and video coverage for track 18 after 7 trawls

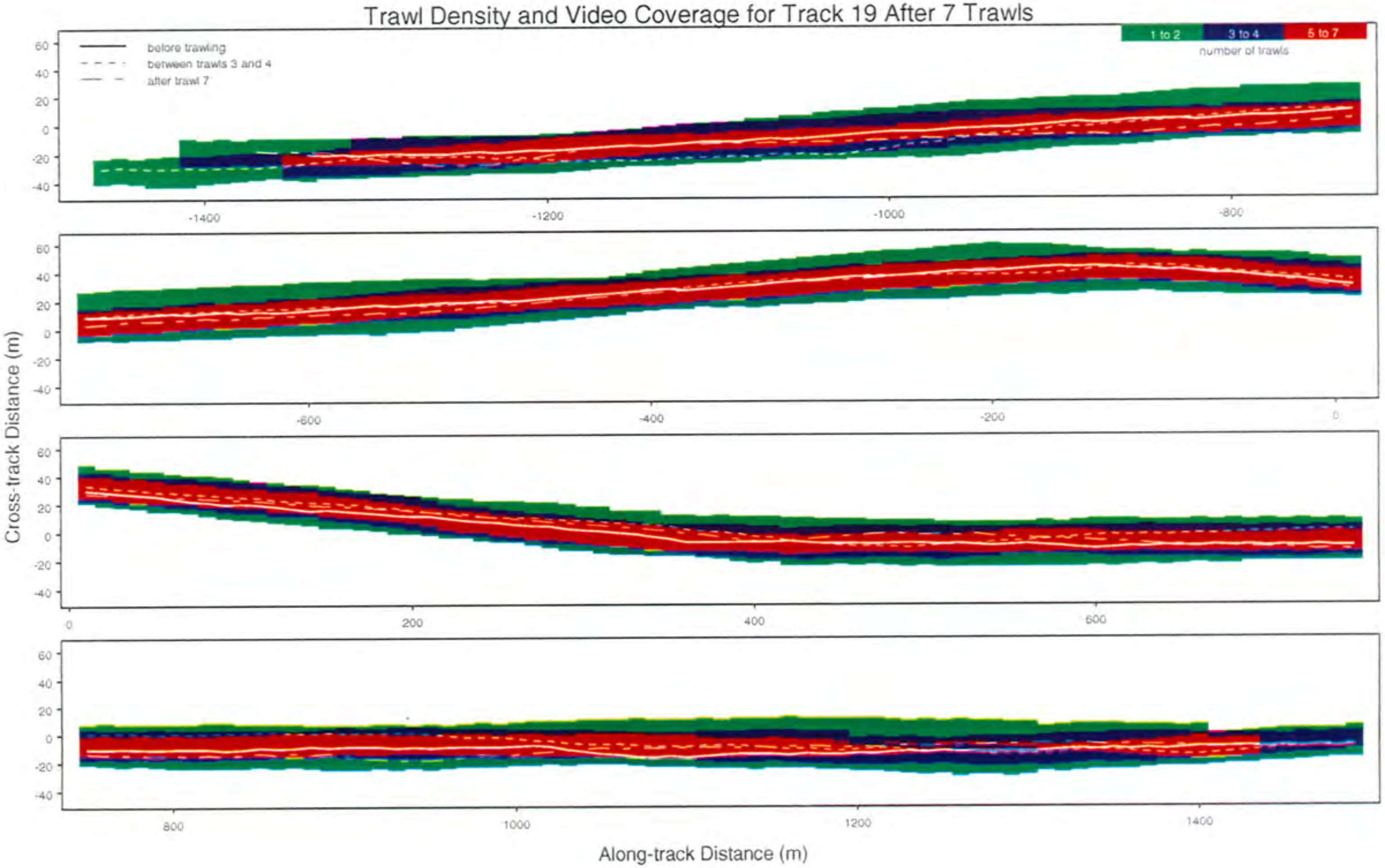


Figure 5.14 Trawl intensity and video coverage for track 19 after 7 trawls

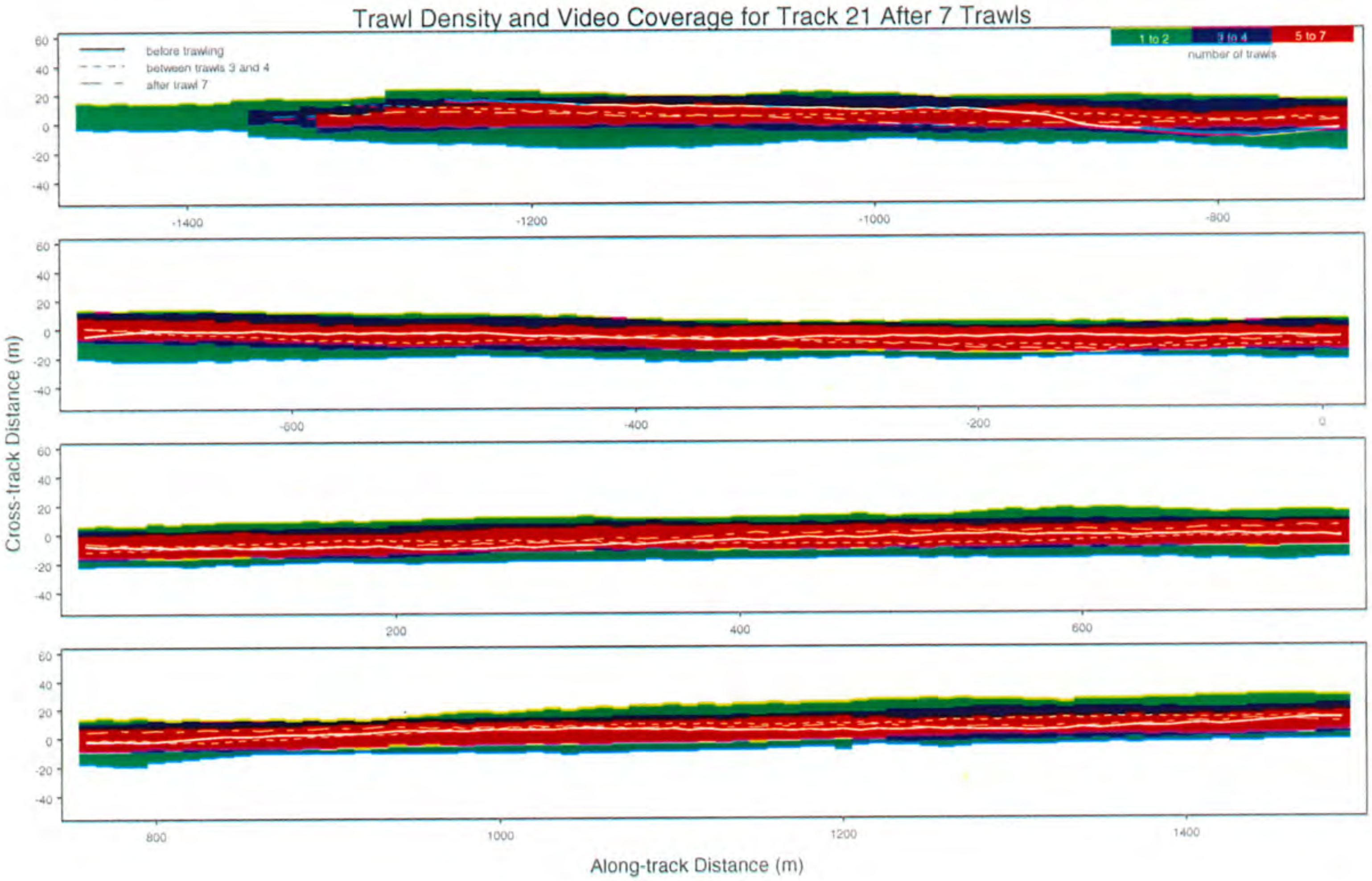


Figure 5.15 Trawl intensity and video coverage for track 21 after 7 trawls

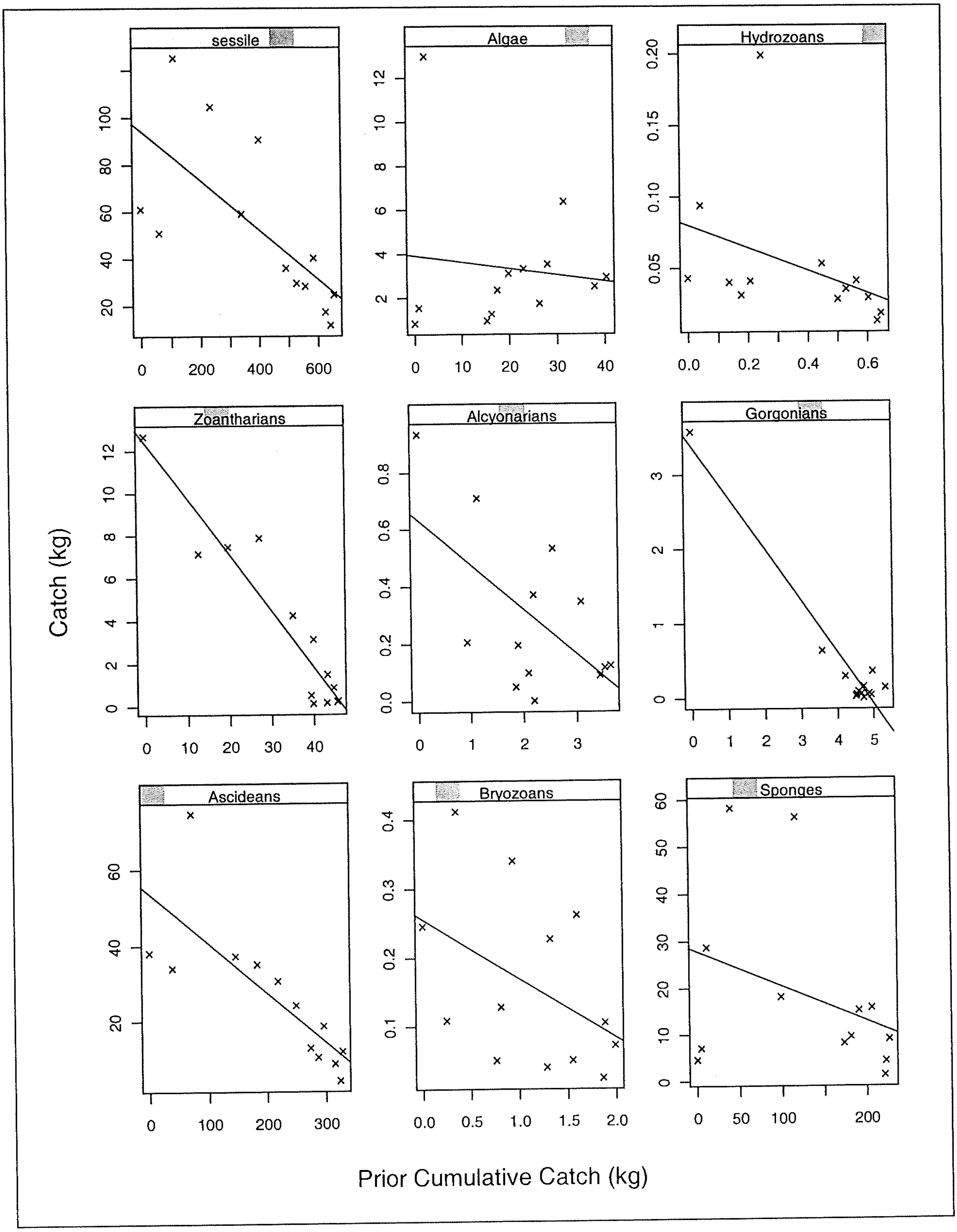


Figure 5.16 Depletion of sessile benthic classes on Track 4

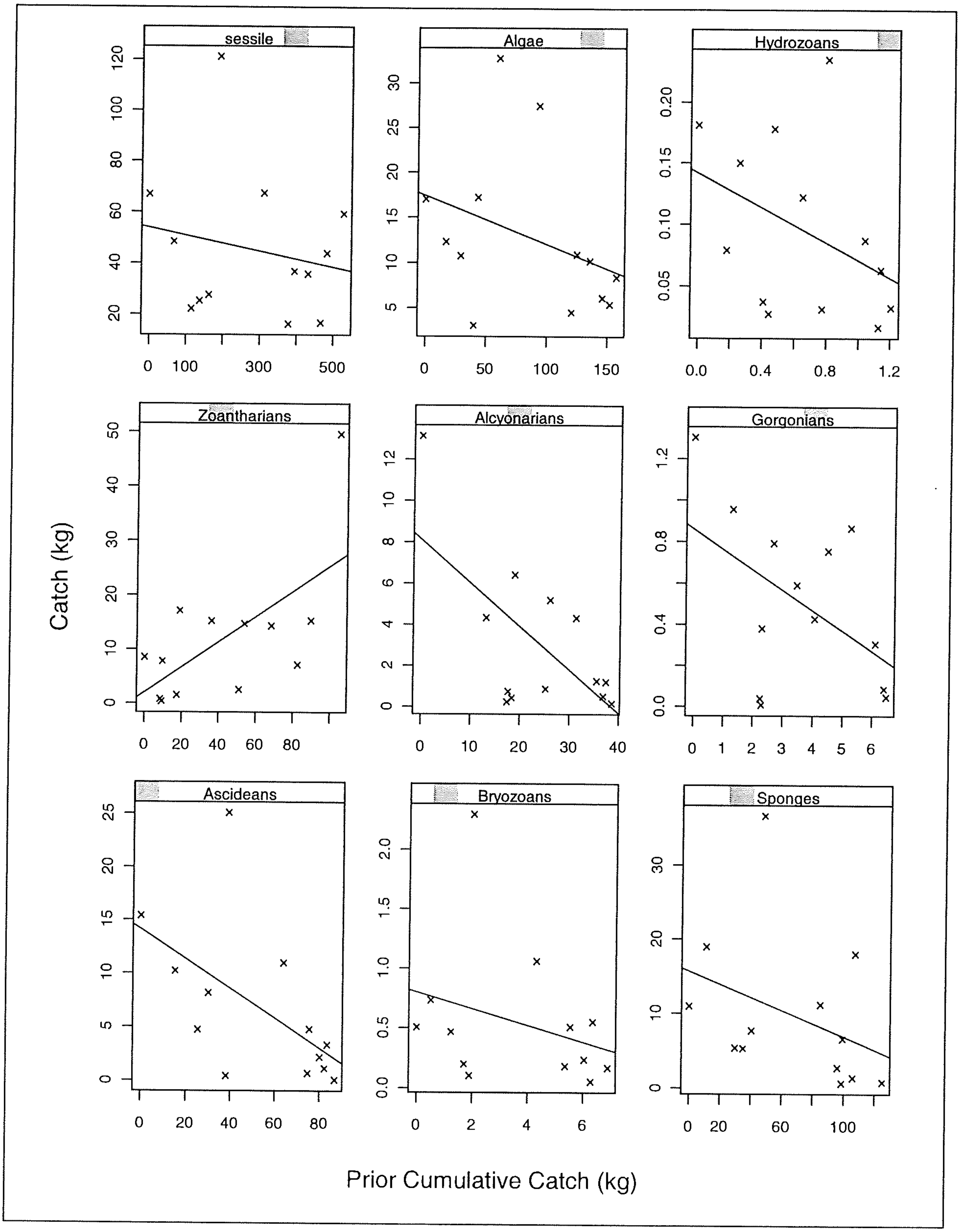


Figure 5.17 Depletion of sessile benthic classes on Track 18

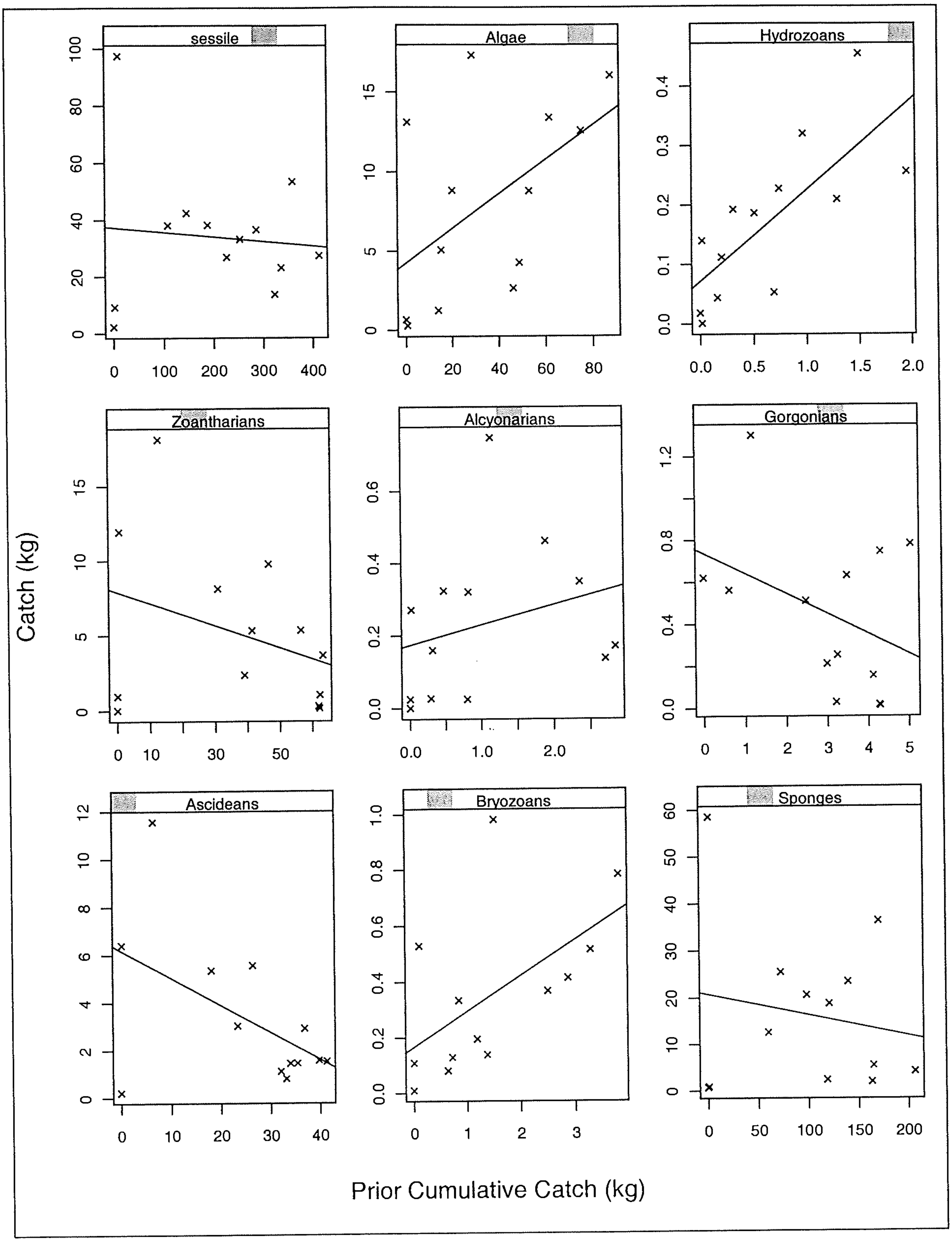


Figure 5.18 Depletion of sessile benthic classes on Track 21

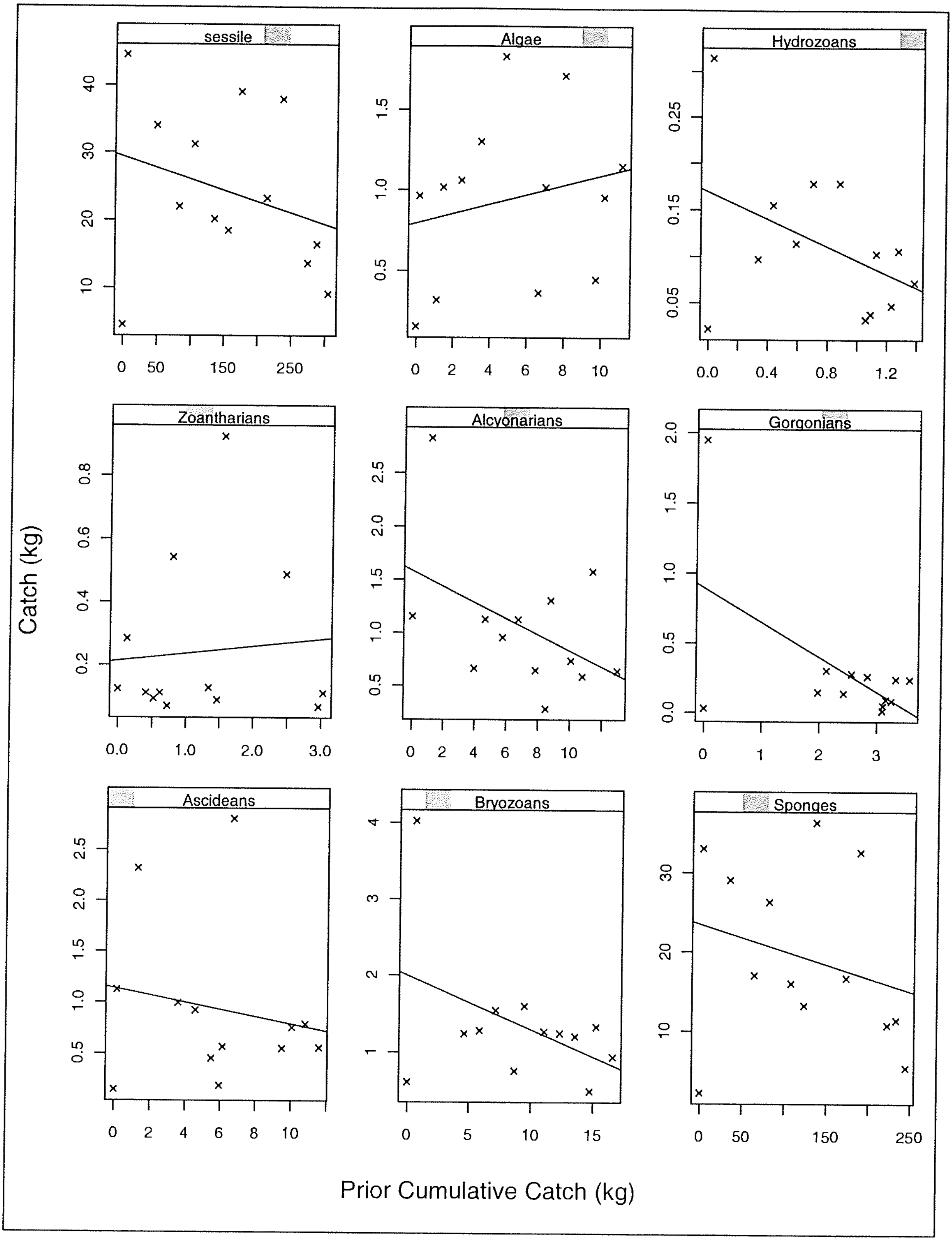


Figure 5.19 Depletion of sessile benthic classes on Track 12

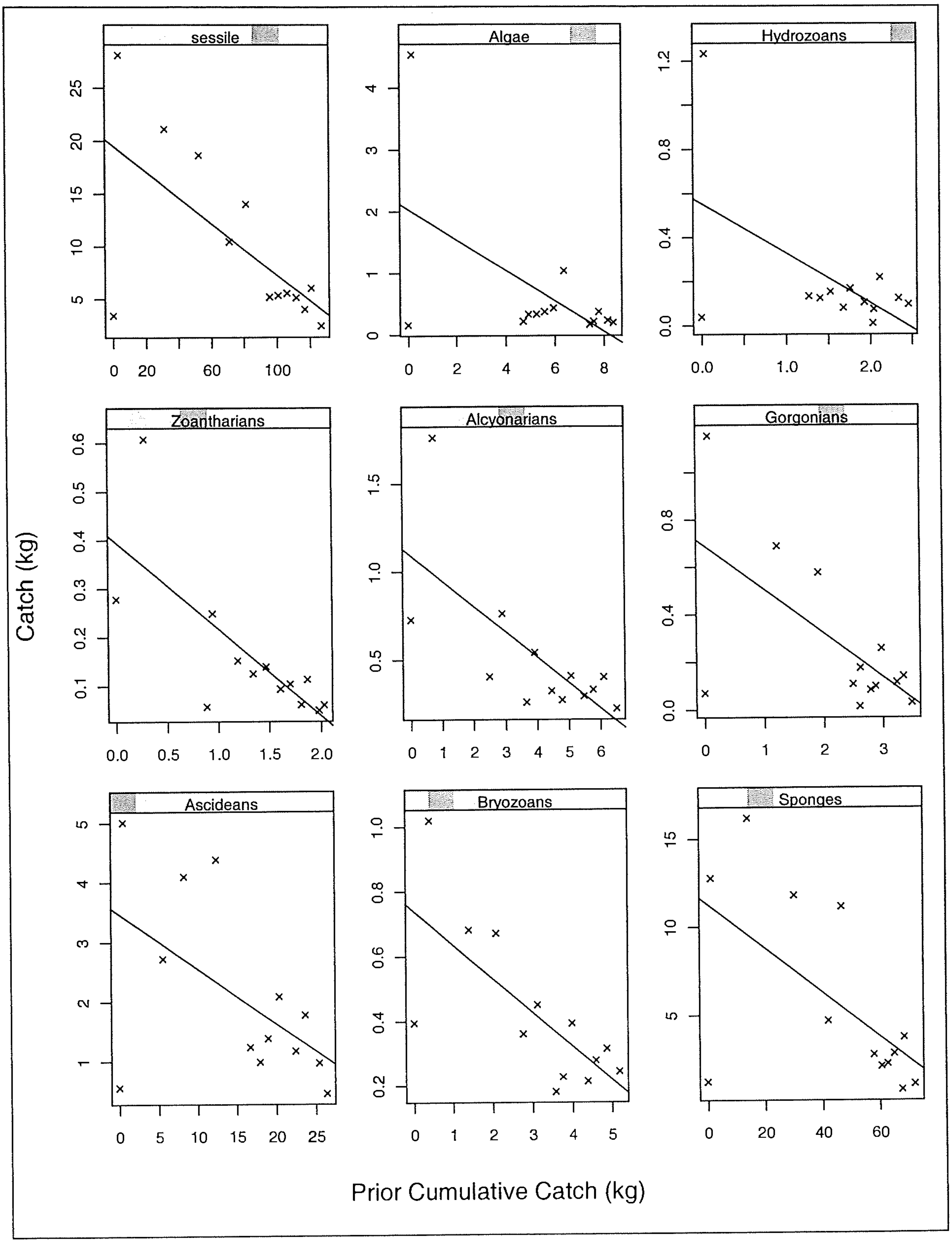


Figure 5.20 Depletion of sessile benthic classes on Track 15

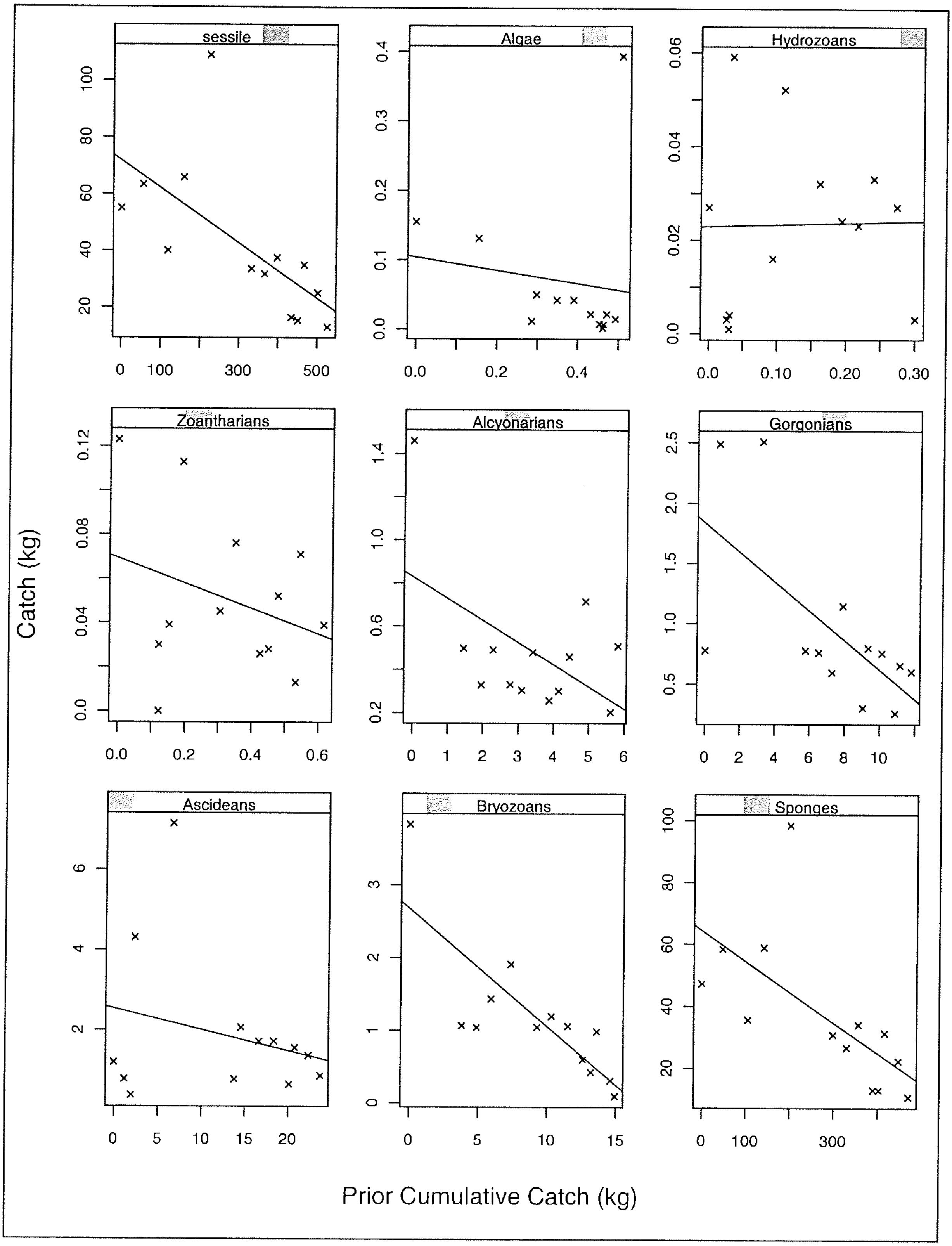


Figure 5.21 Depletion of sessile benthic classes on Track 19

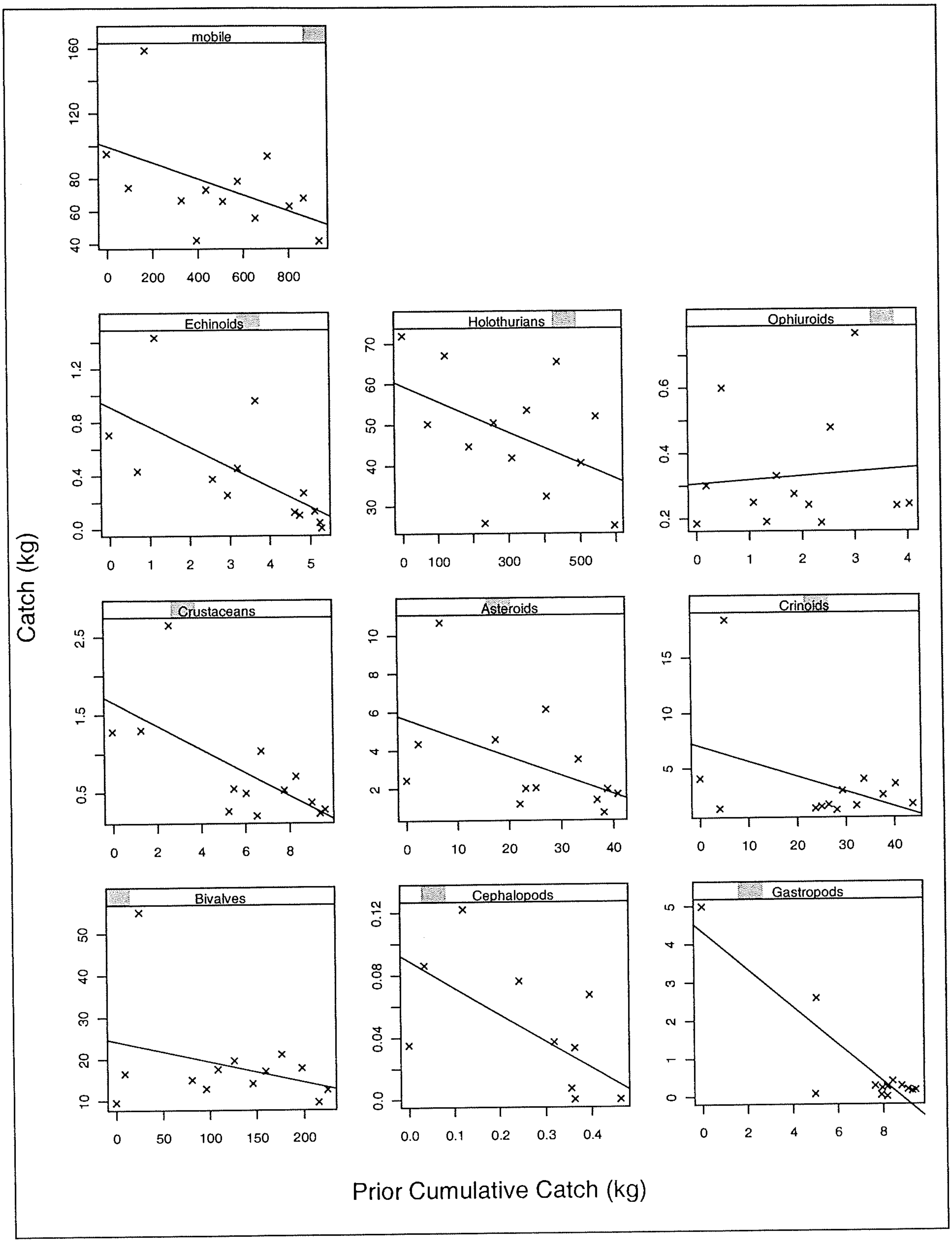


Figure 5.22 Depletion of mobile benthic classes on Track 4

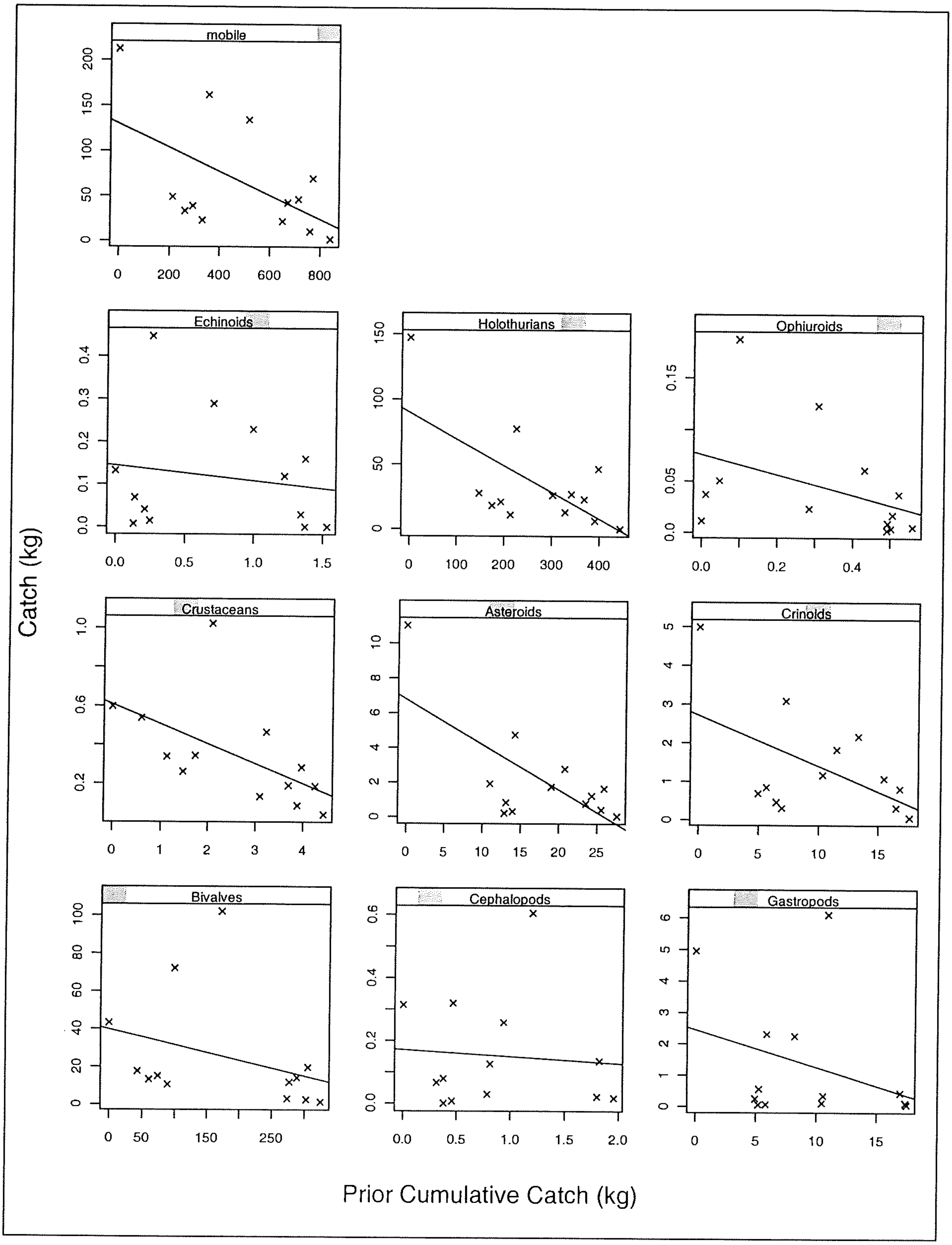


Figure 5.23 Depletion of mobile benthic classes on Track 18

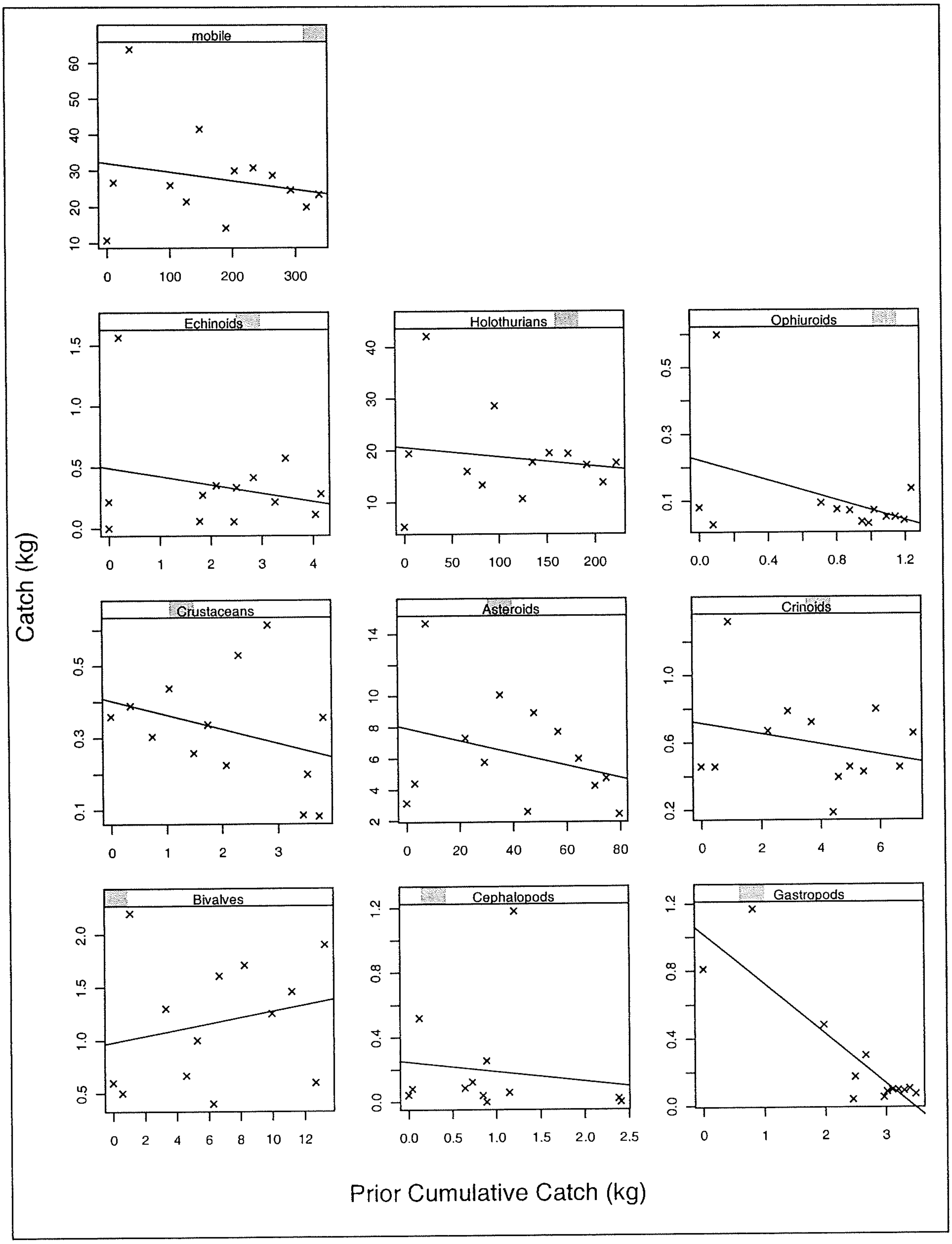


Figure 5.24 Depletion of mobile benthic classes on Track 21

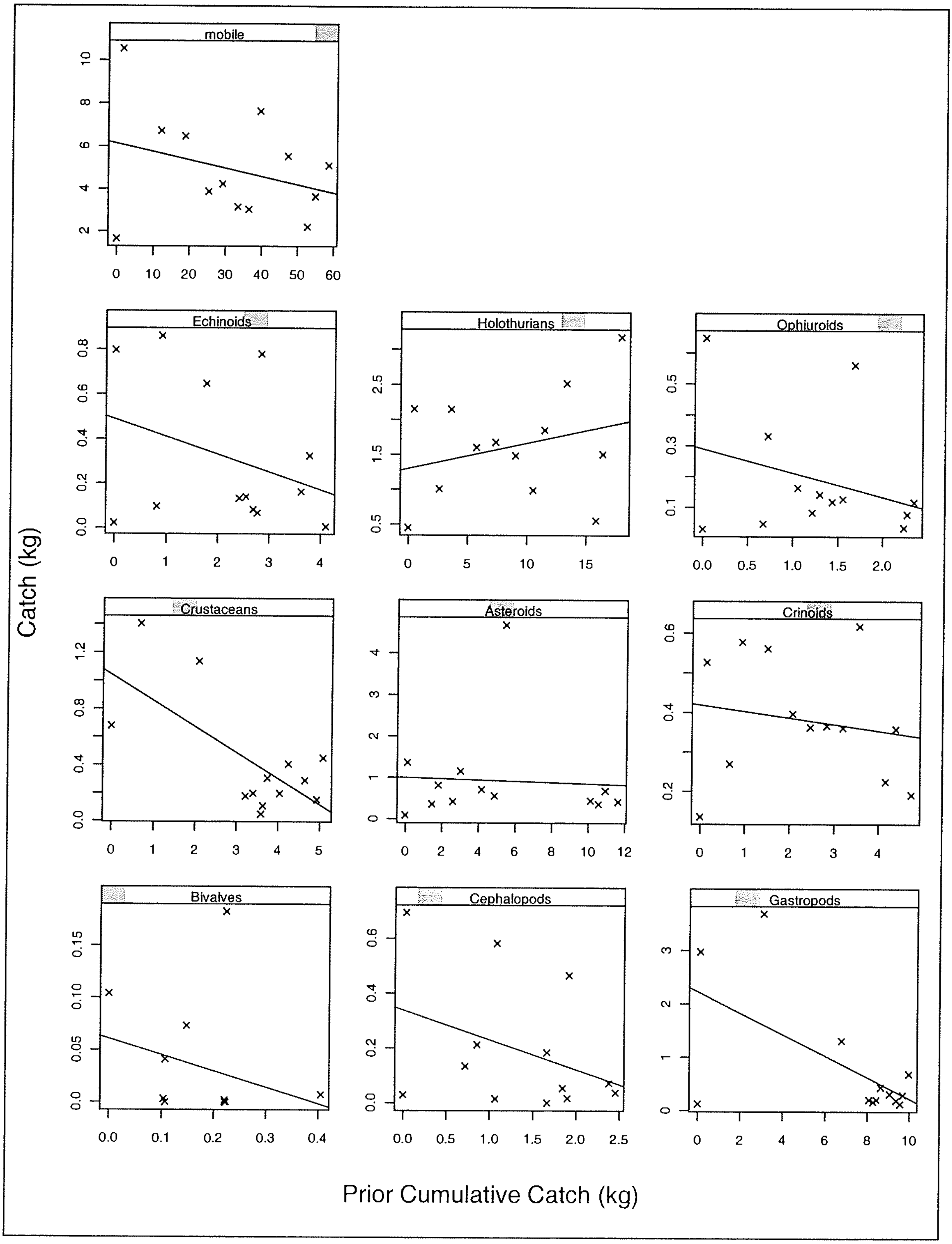


Figure 5.25 Depletion of mobile benthic classes on Track 12

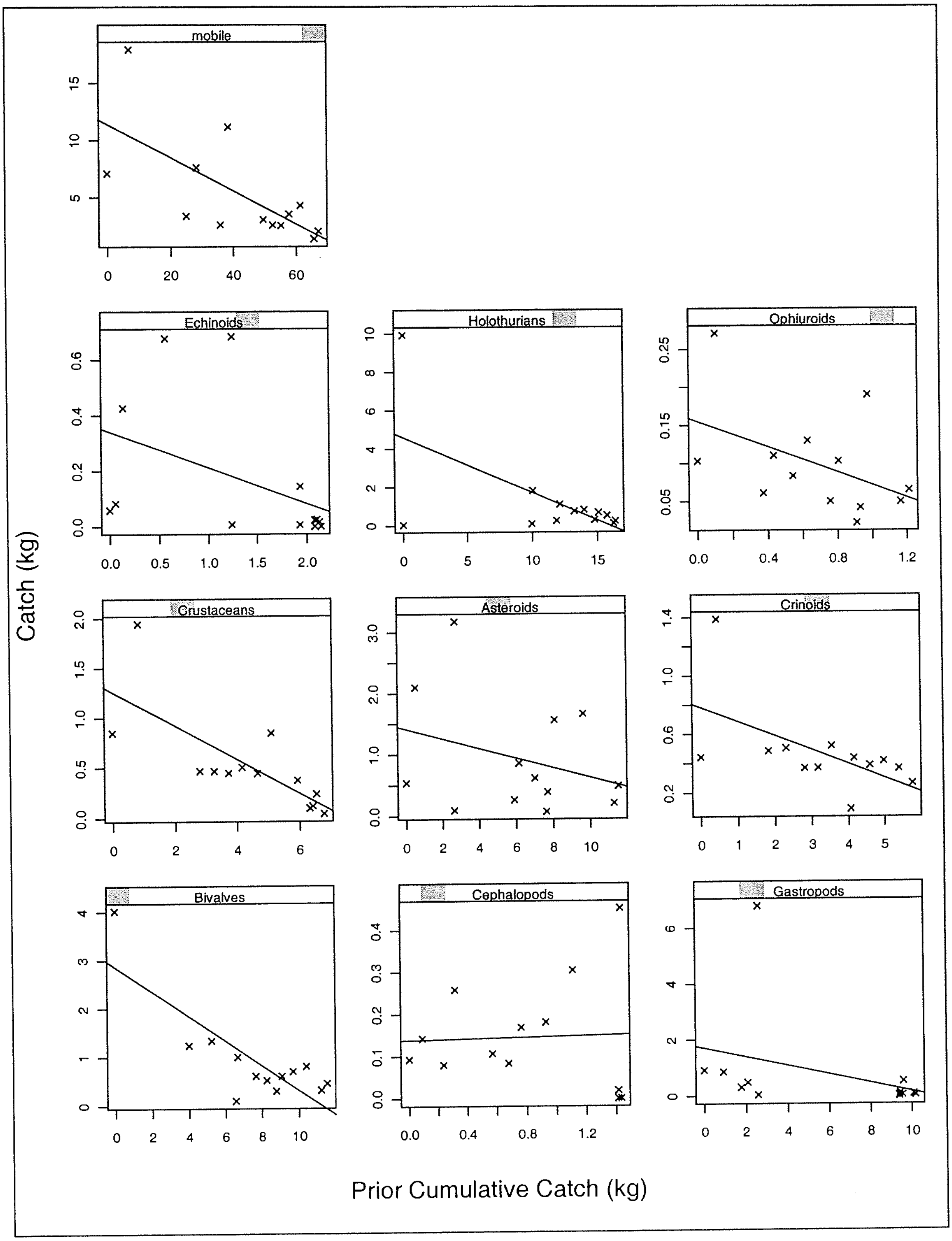


Figure 5.26 Depletion of mobile benthic classes on Track 15

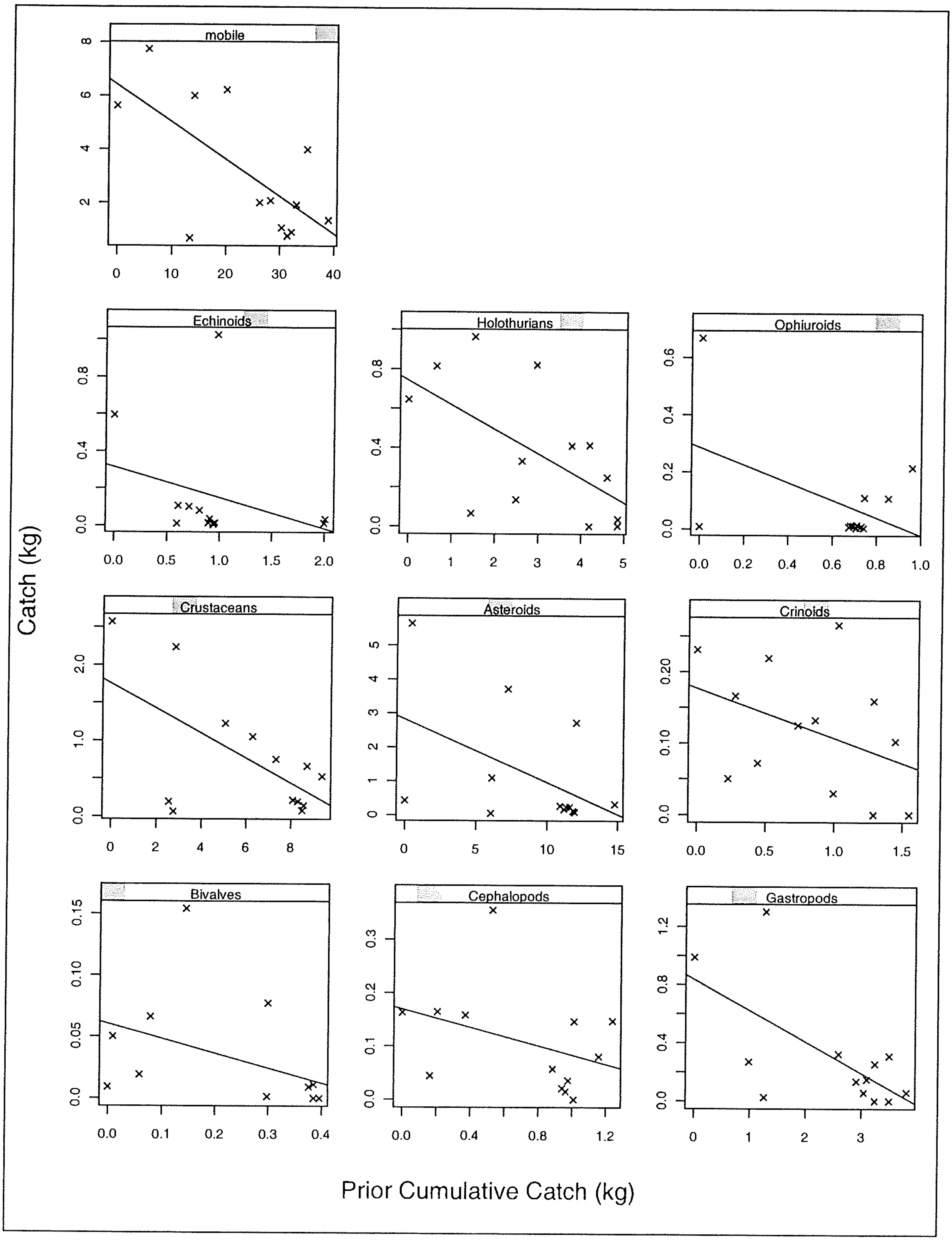


Figure 5.27 Depletion of mobile benthic classes on Track 19

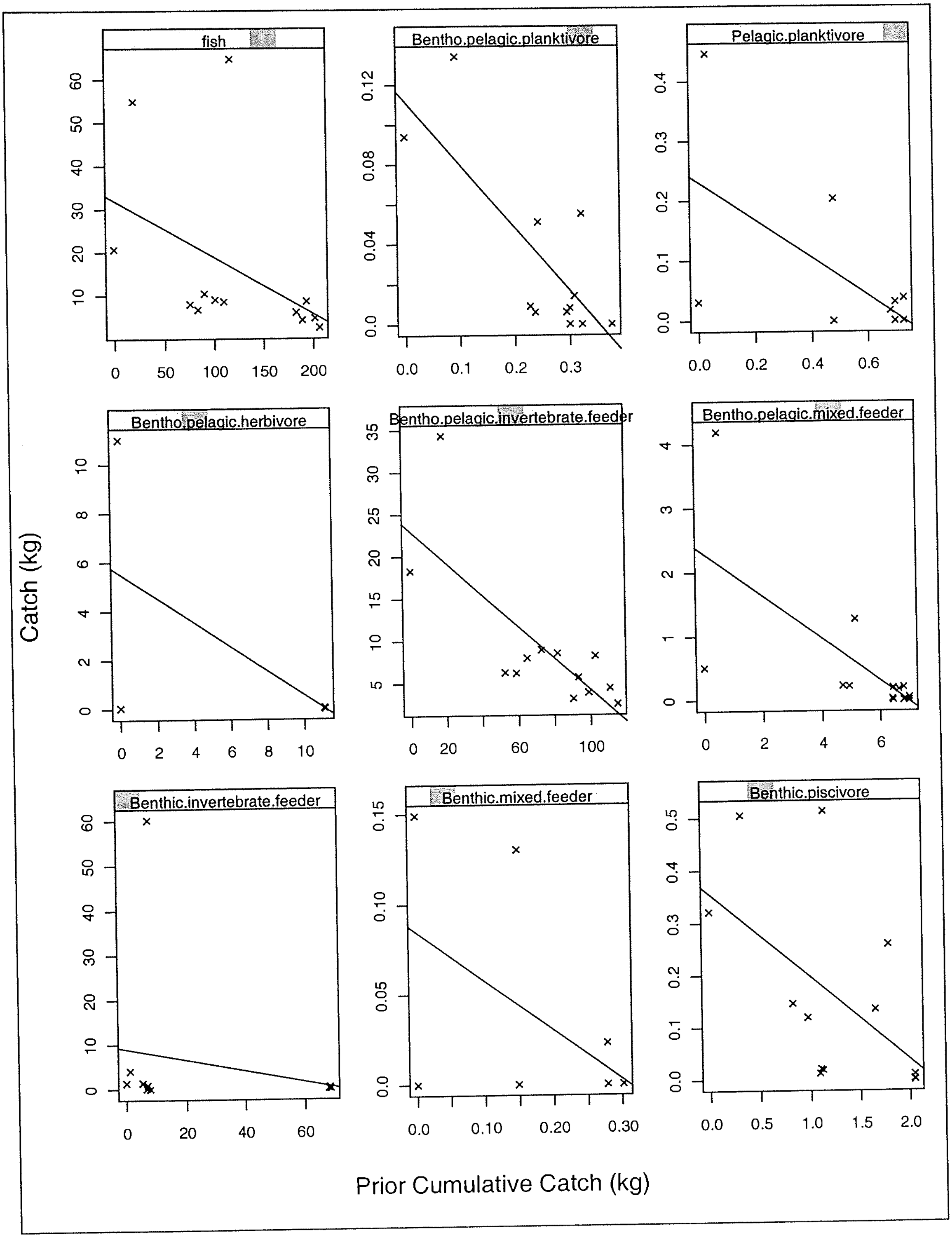


Figure 5.28 Depletion of fish guilds on Track 4

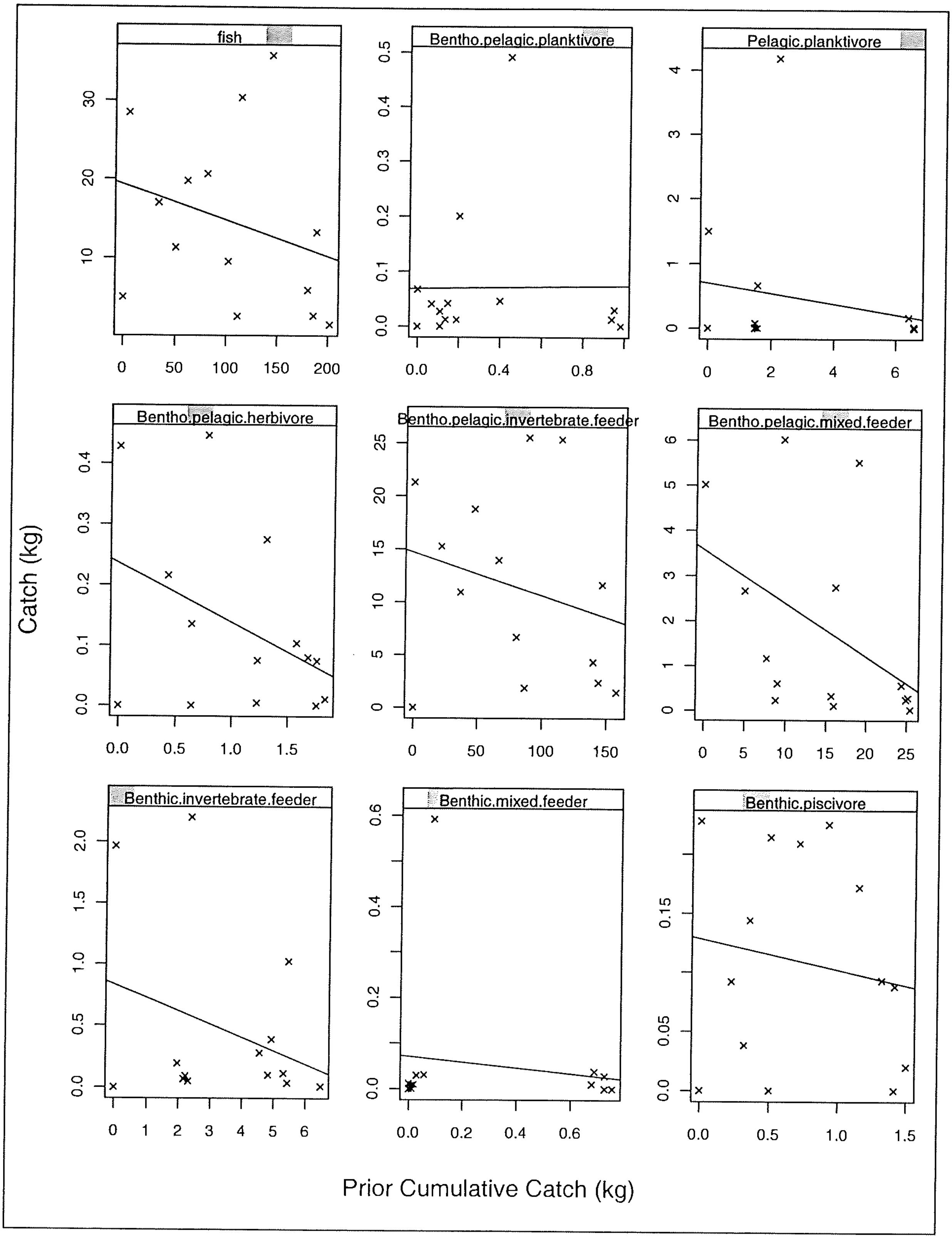


Figure 5.29 Depletion of fish guilds on Track 18

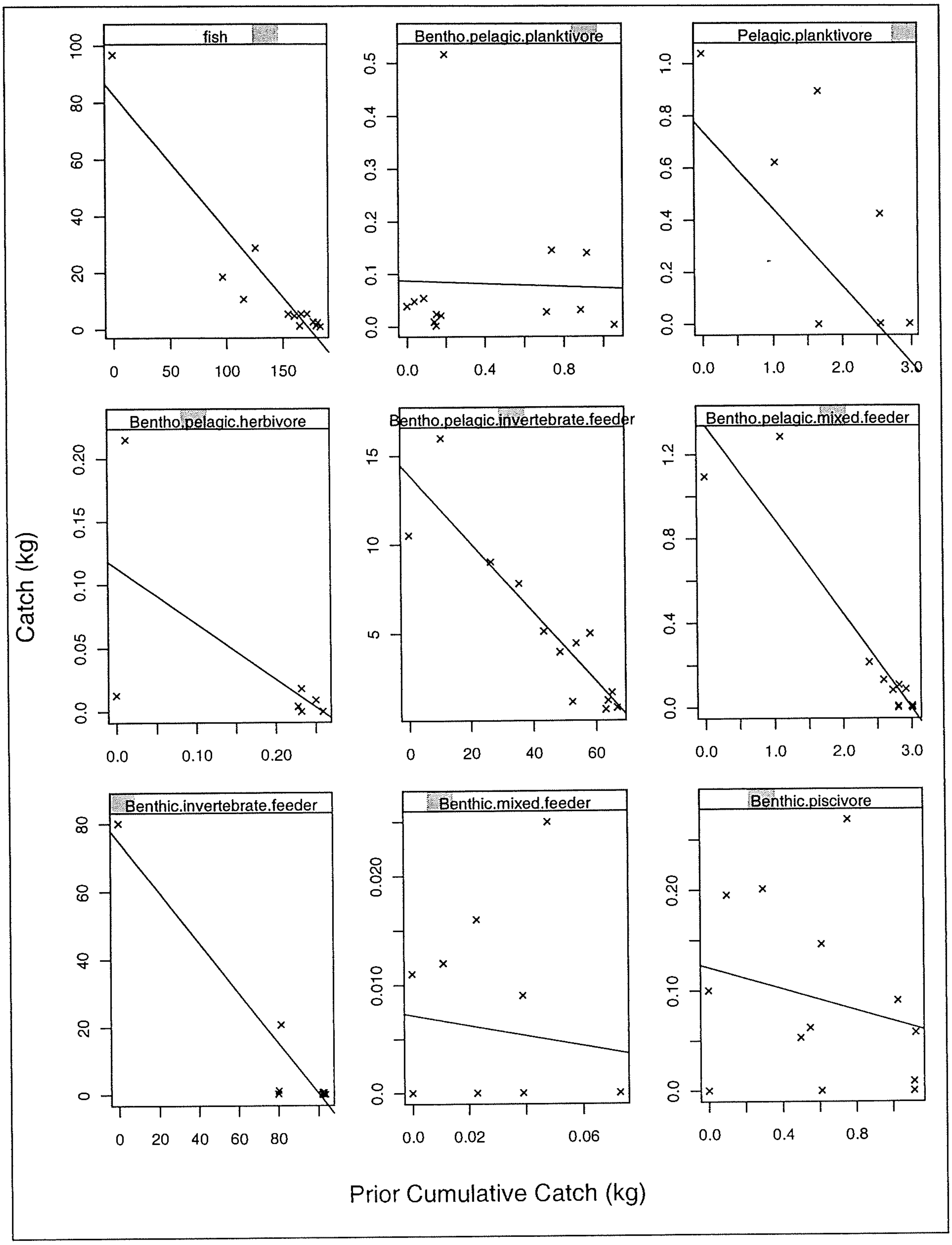


Figure 5.30 Depletion of fish guilds on Track 21

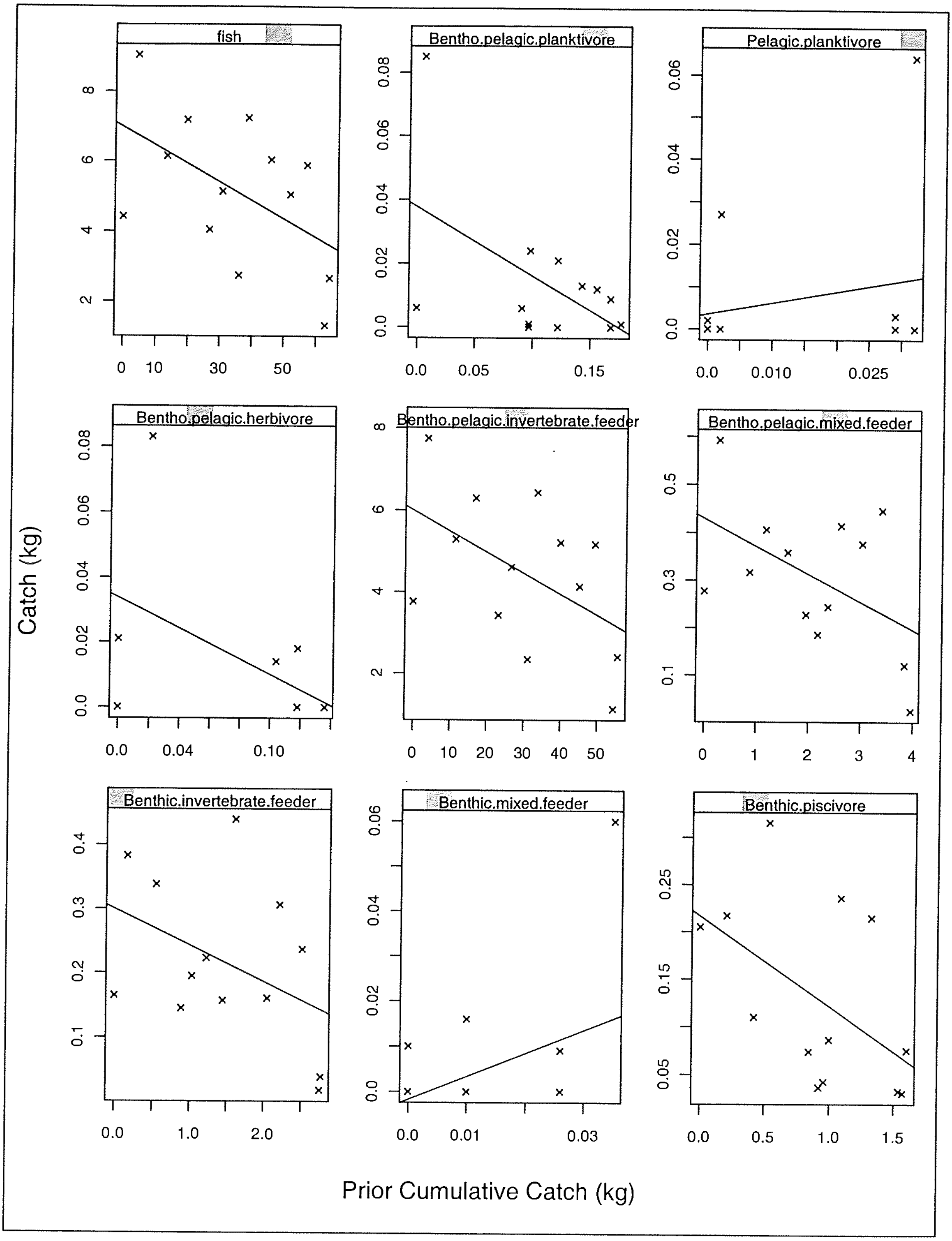


Figure 5.31 Depletion of fish guilds on Track 12

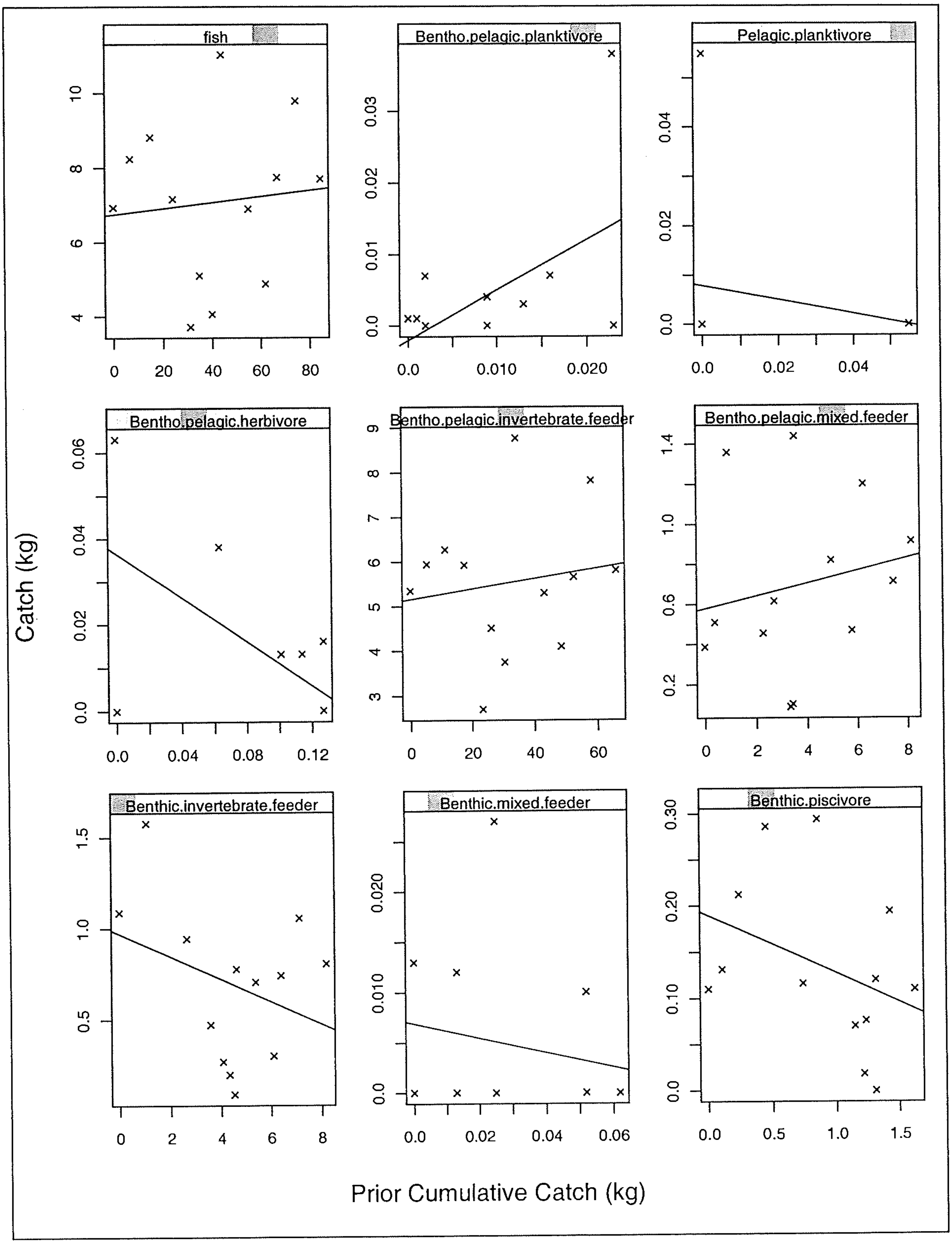


Figure 5.32 Depletion of fish guilds on Track 15

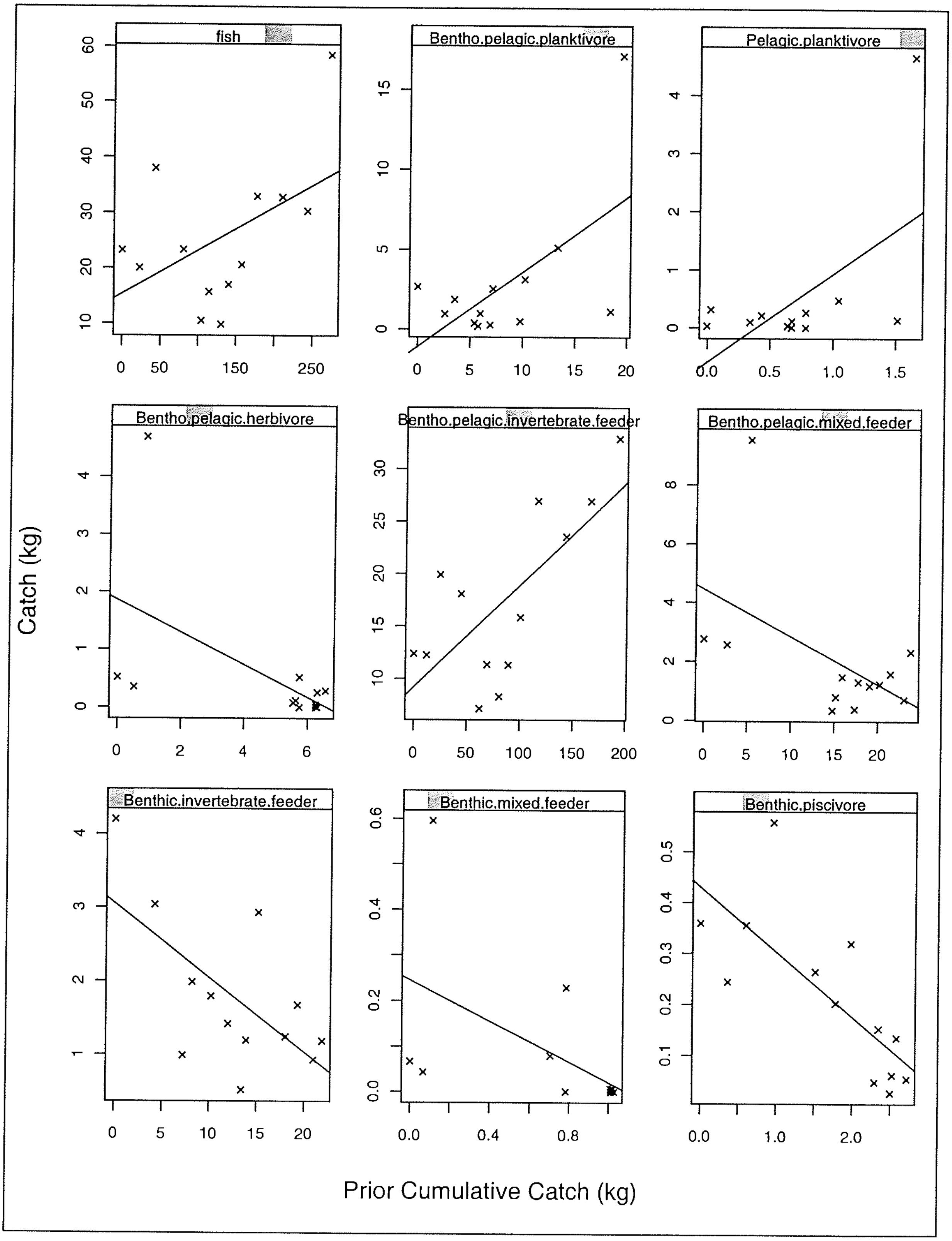
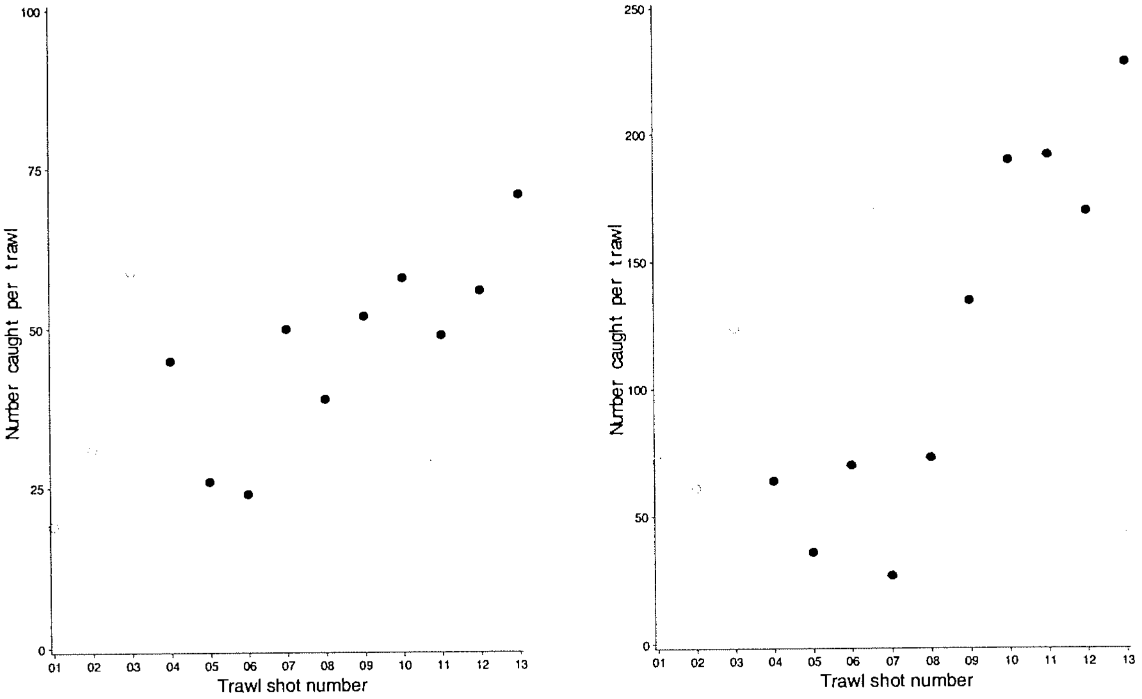


Figure 5.33 Depletion of fish guilds on Track 19



(a) (b)

Figure 5.34 Number of fish caught per trawl during the repeat-trawl depletion experiment on track 19. Species shows are (a) *Nemipterus furcosus* and (b) *Pentapodus paradiseus*. Green circles and red dots indicate trawls done on different days.

APPENDIX.5.A CONVERTING "DEFROSTED" WEIGHTS TO "WET" WEIGHTS

Introduction

This appendix describes the method used to define a correction factor for each benthic class to convert 'defrosted' weights obtained at the Cleveland laboratory into 'wet' weights that would have been obtained at sea.

The calibration was possible because we recorded the bulk weight for broad species groups at sea. This was carried out before each group was partitioned into those items to be processed and discarded at sea and those to be frozen and shipped to Cleveland for processing. Since we know the total 'wet' weight of the catch and the total 'wet' weight of the discards, then in principle we know the total 'wet' weight of the part of the catch sent to Cleveland where the 'defrosted' weight was measured. The ratio of 'wet' to 'defrosted' weight is then the desired correction factor. Since this is likely to vary between organisms, we have calculated a correction factor for each benthic class. For fish there is less variation, and one correction factor has been calculated for all fish.

Method

Let W_{full} be the total bulk wet weight for a certain species group, W_{discard} the 'wet' weight that was identified on board and discarded, and D_{lab} the 'defrosted' weight that was measured at the laboratory. Then we have the following model:

$$W_{\text{full}} = W_{\text{discard}} + \beta D_{\text{lab}} + \varepsilon , \qquad \text{(model A)}$$

where β is the unknown water-loss correction factor and ε is a random component that describes the variability in W_{full}. Since the error in W_{full} is likely to be much larger than the measurement error of W_{discard} and D_{lab}, we assume these weights are measured without error.

We have assumed that ε is normally distributed with zero mean, that the variance depends on group but not on track and trawl, and that all observations are independent. Under these assumptions the problem then reduces to linear regression. Replication is provided by the multiple trawls and tracks. The estimate of β from regression is the unbiased estimate with the least variance.

Twelve of the benthic classes were weighed as bulk groups on board. Five other classes made up most of the remainder, which has been name the 'Others' group. For the latter classes, 'defrosted' weights are available per class but the bulk 'wet' weight is only available for the group as a whole. We can try a more sophisticated analysis based on the following model:

$$W_{\text{full}} - W_{\text{discard}} - D_{\text{lab}} = \beta_{\text{Cep}} D_{\text{Cep}} + \beta_{\text{Cru}} D_{\text{Cru}} + \beta_{\text{Ech}} D_{\text{Ech}} + \beta_{\text{Gas}} D_{\text{Gas}} + \beta_{\text{Oph}} D_{\text{Oph}} + \varepsilon ,$$

(model B)

In this model, D_{Cep} is the 'defrosted' weight of cephalopods and β_{Cep} is the water-loss factor: if no water loss occurred, this value would be 0; if water loss occurred, the value would exceed 0. This formulation of the model makes it easier to test the estimates against a null hypothesis of $\beta = 0$ (or a wet-to-defrosted ratio of 1).

Results

The results of the regression analysis are shown in Table App.5.A.1. These are based on the groupings used for on-board bulk weighing. In most cases there is bulk weight for each class, but a few classes are represented collectively in the "Others" group. This group consisted mainly of cephalopods, crustaceans, echinoids, gastropods and ophiuroids for which class weights were generally small. In addition, small individuals from the groups corresponding to classes (e.g. zoantharians) will probably have been placed in the "Others" group.

The "factor" is the estimate of β, the factor by which defrosted weights are multiplied to give equivalent wet weights. The "SE" column gives the standard error of the estimate of β. The p values and the associated degrees of freedom are shown in the next columns.

Table App.5.A.1 Water-loss correction factors by species group, from model A.

Group	factor	SE	*p*	df
Alcyonarians	1.81	0.11	<.00001	65
Algae	1.66	0.02	<.00001	65
Ascidians	1.15	0.06	<.00001	59
Asteroids	1.65	0.14	<.00001	67
Bryozoans	1.60	0.05	<.00001	68
Crinoids	1.13	0.01	<.00001	75
Fish	1.04	0.01	<.00001	77
Gorgonians	3.98	2.08	.06078	51
Holothurians	1.65	1.06	.15257	9
Hydrozoans	1.26	0.07	<.00001	23
Sponges	1.31	0.05	<.00001	73
Zoantharians	1.58	0.71	.05500	8
Others	2.19	0.16	<.00001	76

The data are displayed in Figure App.5.A.1. For each bulk weight grouping we plot (W_{full} – $W_{discard}$) *vs* D_{lab}. The regression line through the origin is overlaid. From now on we refer to the quantity W_{full} – $W_{discard}$ simply as *the wet weight* (of the catch processed at the Cleveland laboratory) and D_{lab} as *the defrosted weight.*

There are a few instances of a negative weight, which arose from inaccuracies of on-board weighing and recording. The trawl deck is an environment that is not conducive to precise sorting and measuring, which is why nearly all of the catch was sent to the Cleveland laboratory for detailed processing.

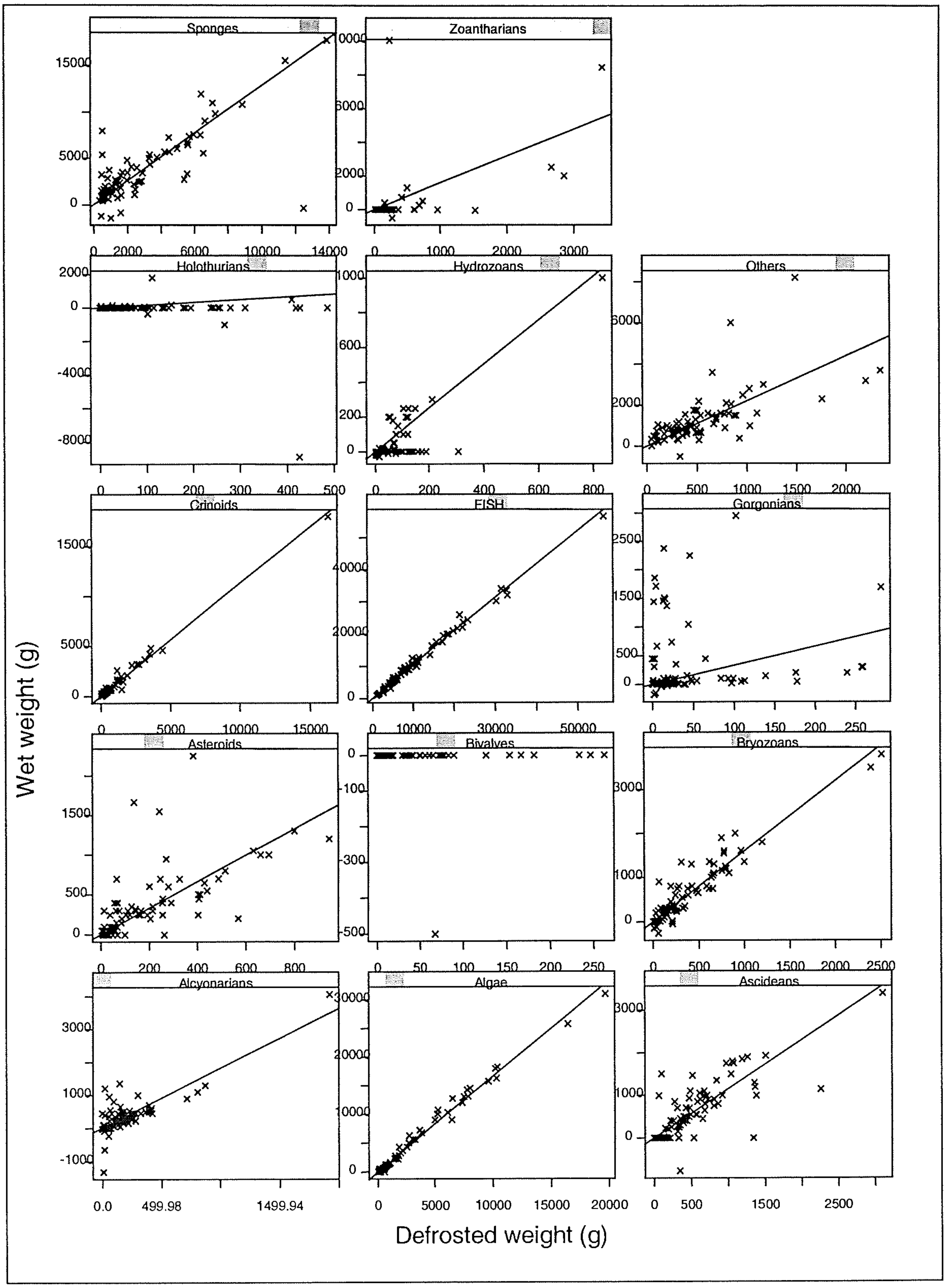


Figure App.5.A.1 Wet versus defrosted weights for each species group. The regression line through the origin is also shown.

From Figure App.5.A.1, it can be seen that there are clear-cut wet-to-defrosted relationships for algae, crinoids and fish. This is confirmed by the highly significant *p* values in Table App.5.A.1. For bryozoans and sponges the relationship is also very well defined and there is a reasonable relationship for alcyonarians, ascidians, asteroids and hydrozoans. For the Others group, the data plotted in Figure 1 suggest that there is a mixture of slopes for the classes that form the major components of this group. It is therefore appropriate to apply the more sophisticated approach described in the Methods section of this appendix.

The hydrozoans have a highly influential observation at 800 g defrosted weight. When this observation is removed, the estimate of β increases to 1.47, a substantial change well beyond 2 standard errors. The influential point comes from track 15 trawl 2, where an extra-large individual with a defrosted weight of 381 g was caught; it was over twice the defrosted weight of any other hydrozoan at the Cleveland laboratory. This suggests that the wet-to-defrosted relationship may not be linear over the entire range and that less water loss occurs for larger hydrozoans. (However, a quadratic term added to the model was not significant.)

There is no estimate for bivalves because, apart from isolated individuals that may have been included in the Others group, these were bulk-weighed on board and discarded. Therefore all the wet weights are zero. The small defrosted weights that appear (< 250 g, see Figure App.5.A.1) have most likely come from the (wet) Others group. These defrosted weights are considered too small for it to be worth fitting a calibration model.

For holothurians and zoantharians there are too few observations to define any relationship. As with the bivalves, most were bulk-weighed and discarded. Most of the defrosted weights come from small individuals in the Others group.

The gorgonians present a problem. According to Figure App.5.A.1, large quantities of gorgonians (around 1.5 kg) were brought to the laboratory, but only small amounts (less than 100 g) turned up in the defrosted weights. This is unlikely to be due to the gorgonians being incorrectly identified on the boat. A more likely explanation is that during the bulk weighing they could have retained a lot of surface water, due to their physical structure, which would have exaggerated their weight. After some time on deck, they were identified nad packaged for the laboratory. By this time, the water would have run off and they would be much lighter.

The data for the Others group are plotted in Figure App.5.A.2. We applied a stepwise regression to the Others data, initially using model B, to arrive at a simpler model consisting of the three terms Crustaceans, Echinoids and Gastropods. The βs for Cephalopods and Ophiuroids were not significantly different from zero (see the regression lines in Figure App.5.A.2). Two influential points were deemed to be outliers and discarded; these are the two points with largest wet weights in each plot of Figure App.5.A.2. Discarding these points from model A led to a revised estimate of 1.88.

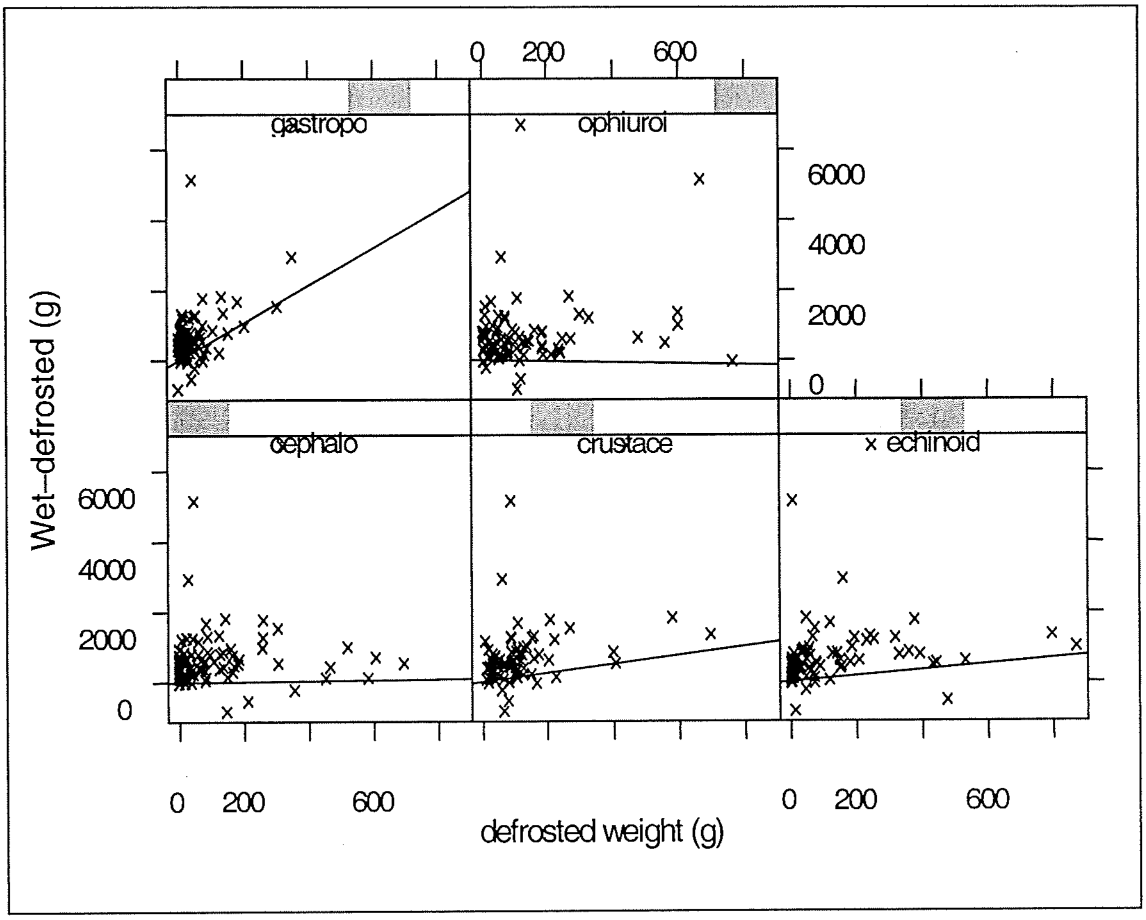


Figure App.5.A.2 **Excess total wet weight over total defrosted weight *vs* defrosted weight in each class for the Others group. Overlaid is the line representing the contribution of each class to the full linear model. All plots are on the same scale.**

The resulting factor estimates for the five major classes that comprise the Others group are shown in Table App.5.A.2. The standard errors are rather large and the factor for Gastropods is higher than expected. However, the residual standard error is down to 463 g compared to 950 g for the Others group as a whole (see Table App.5.A.1) and the R^2 value is 89%.

Table App.5.A.2 **Water-loss correction factors for the classes within the Others group.**

Class	Factor	SE	*p*
Crustaceans	2.23	0.50	.0169
Echinoids	1.80	0.33	.0163
Gastropods	6.41	0.86	<.0001
Cephalopods	1.00		
Ophiuroids	1.00		

Conclusions

For just over half of the species groups we have a reliable estimate of the water-loss factor. For the five classes in the Others group we have somewhat less reliable estimates, with larger standard errors. For the remaining four classes we have no estimate at all.

It makes sense to convert to wet weights whenever possible since these relate to the organism in its natural habitat. For the "reliable" groups we multiply up the defrosted weights by the estimated factor. For the groups with no estimate we use a factor of 1, (i.e. we assume no water loss). This is not a big problem because the defrosted weights for these species are very small anyway. The bulk of these species were processed on the boat, so we have accurate wet weights for them.

Potentially the most problematic are the classes in the Others group. We have estimates for these, but the standard errors are moderately large. It is, however, important to use a sensible conversion factor because a large proportion of this group was processed at the laboratory and a small proportion on board. We shall use the best estimates available: those given in Table App.5.A.3.

Table App.5.A.3 presents the final values chosen for conversion of defrosted weights to wet weights, together with an indication of the reliability of the estimate.

Table App.5.A.3 Final values for wet-to-defrosted factor

Species Group	Reliable estimate?	Factor
Alcyonarians	yes	1.81
Algae	yes	1.66
Ascidians	yes	1.15
Asteroids	yes	1.65
Bryozoans	yes	1.60
Crinoids	yes	1.13
Fish	yes	1.04
Hydrozoans	yes	1.47
Sponges	yes	1.31
Cephalopods	maybe	1.00
Crustaceans	maybe	2.23
Echinoids	maybe	1.80
Gastropods	maybe	6.41
Ophiuroids	maybe	1.00
Bivalves	no	1.00
Gorgonians	no	1.00
Holothurians	no	1.00
Zoantharians	no	1.00

APPENDIX.5.B GROUPING OF FISH SPECIES INTO HABITAT/FEEDING GUILDS

Benthic-invertebrate

Amphiprion clarkii, Amphotistius kuhlii, Aptychotrema sp., *Arnoglossus waitei, Callionymus grossi, Callionymus japonicus, Callionymus limiceps, Chiloscyllium punctatum, Crossorhombus azureus, Crossorhombus* sp., *Cynoglossus* sp., *Dactyloptena orientalis, Dactylopus dactylopus, Dascyllus trimaculatus, Dasyatis leylandi, Dasyatis thetidis, Engyprosopon grandisquama, Engyprosopon macroptera, Eurypegasus draconis, Gobiidae* sp., *Grammatobothus polyophthalmus, Gymnura australis, Himantura granulata, Himantura* sp. (Leopard), *Himantura toshi, Himantura uarnak, Nebrius concolor, Ophidion muraenolepis, Parapercis nebulosa, Parapercis snyderi, Pardachirus pavoninus, Parupeneus chrysopleuron, Parupeneus spilurus, Pastinachus sephen, Pseudaesopia japonica, Pseudamia gelatinosa, Pseudorhombus dupliciocellatus, Pseudorhombus quinquocellatus, Pseudorhombus argus, Pseudorhombus diplospilus, Pseudorhombus jenynsii, Pseudorhombus spinosis, Rhina ancylostoma, Rhynchobatus djiddensis, Samaris cristatus, Sillago ingennua, Sillago robusta, Sillago sihama, Stegostoma fasciatum, Synchiropus rameus, Taeniura lymna, Upeneus asymmetricus, Upeneus luzonius, Upeneus tragula, Urogymnus asperrimus, Zebrias craticula*

Benthic-mixed

Adventor elongatus, Atelomycterus sp. A, *Cymbacephalus nematophthalmus, Elates ransonetti, Engyprosopon* sp., *Erosa erosa, Euristhmus nudiceps, Lepidotrigla argus, Onigocia oligolepis, Onigocia spinosa, Platycephalus endrachtensis, Plotosus lineatus, Sorsogona tuberculata, Suggrundus isacanthus, Suggrundus japonicus, Tathicarpus butleri*

Benthic-piscivorous

Antennarius hispidus, Apistus carinatus, Centrogenys vaigiensis, Coccotropus spp., *Dendrochirus brachypterus, Dendrochirus zebra, Gymnothorax* sp., *Halophryne diemensis, Halophryne ocellatus, Inimicus caledonicus, Liocranium praepositum, Liocranium scorpio, Lophiocharon trisignatus, Meiacanthus grammistes, Meiacanthus luteus, Minous coccineus, Minous trachycephalus, Paracentropogon longispinis, Peristominous dolosus, Platycephalus indicus, Pontinus tentacularis, Pterois volitans, Saurida gracilis, Saurida micropectoralis, Saurida* sp.2, *Saurida undosquamis, Scorpaenopsis venosa, Suggrundus bosschei, Suggrundus staigeri, Synodus hoshinonis, Synodus indicus, Synodus jaculum, Synodus sageneus, Synodus variegatus, Tetraroge leucogaster, Trachinocephalus myops*

Benthopelagic-herbivorous

Acanthurus grammoptilus, Calotomus carolinus, Naso annulatus, Naso brevirostris, Naso tuberosus, Platax batavianus, Platax teira, Scarus chameleon, Scarus ghobban, Siganus argenteus, Siganus canaliculatus, Siganus fuscescens

Benthopelagic-invertebrate

Abalistes stellaris, Acanthochromis polyacanthus, Aetobatus narinari, Aetomyleus vespertilio, Alepes sp., *Alutera monoceros, Aluterus scriptus, Amblypomacentrus breviceps, Amblyrhynchotes spinosissimus, Anchisomus multistriatus, Arothron aerostaticus, Arothron hispidus, Arothron immaculatus, Arothron manillensis, Arothron reticularis, Arothron stellatus, Atule mate, Balistoides viridescens, Canthigaster compressa, Canthigaster coronata, Canthigaster rivulata, Canthigaster valentini, Chaetoderma penicilligera, Chaetodontoplus duboulayi, Chaetodontoplus meredithi, Cheilinus bimaculatus, Chelmon marginalis, Chelmon rostratus, Choerodon sugillatum, Choerodon cephalotes, Choerodon frenatus, Choerodon monostigma, Choerodon shoenleinii, Choerodon* sp. 2, *Choerodon vitta, Chromis atripectoralis, Chrysiptera flavipinnis, Coradion altivelis, Coradion chrysozonus, Coris pictoides, Cyclichthys jaculiferus, Cymolutes torquatus, Dascyllus aruanus, Diagramma pictum, Diodon hystrix, Diodon liturosus, Fistularia commersonii, Fistularia petimba, Gerres filamentosus, Gerres oyena, Gymnocranius robinsoni, Halichoeres zeylonicus, Lactoria cornutus, Lactoria fornasini, Lagocephalus lunaris, Lagocephalus sceleratus, Myripristis hexagona, Myripristis melanostictus, Myripristis murdjan, Nemipterus furcosus, Nemipterus peronii, Neopomacentrus cyanomos, Ostracion cubicus, Parachaetodon ocellatus, Paramonacanthus cingalensis, Paramonacanthus choirocephalus, Paramonacanthus japonicus, Parastromateus niger, Parupeneus heptacanthus, Parupeneus indicus, Pelates quadrilineatus, Pentapodus nagasakiensis, Pentapodus paradiseus, Pentapodus sp., Plectorhynchus gibbosus, Pomacanthus sexstriatus, Pomacentrus moluccensis, Pomacentrus nigromarginatus, Pristotis jerdoni, Pseudobalistes fuscus, Pseudocheilinus evanidus, Pseudochromis quinquedentatus, Pseudomonacanthus elongatus, Pseudomonacanthus peroni, Pteragogus amboinensis, Rhynchostracion rhinorhynchus, Rhynchostracion nasus, Rudarius excelsus, Scolopsis affinis, Scolopsis monogramma, Scolopsis taeniopterus, Siphamia* Sp., *Siphamia argyrogaster, Siphamia guttulatus, Solenostomus cyanopterus, Terapon jarbua, Tetrosomus gibbosus, Thalassoma lunare* (Linnaeus), *Torquigener brevipinnis, Torquigener hicksi, Torquigener pallimaculatus, Xyrichthys aneitensis, Xyrichthys jacksonensis*

Benthopelagic-mixed

Alectis ciliaris, Carangoides caeruleopinnatus, Carangoides chrysophrys, Carangoides fulvoguttatus, Carangoides gymnostethus, Carangoides hedlandensis, Carangoides humerosus, Carangoides talamparoides, Caranx bucculentus, Cephalopholis boenack, Cottapistus cottoides, Cyprinocirrhites polyactis, Epinephelus areolatus, Epinephelus malabaricus, Gnathanodon speciosus, Gymnocranius grandoculis, Lethrinus genivittatus, Lethrinus laticaudus, Lethrinus lentjan, Lethrinus nebulosus, Lethrinus semicinctus, Lethrinus xanthochilus, Lutjanus carponotatus, Lutjanus fulviflamma, Lutjanus kasmira, Lutjanus lutjanus, Lutjanus malabaricus, Lutjanus quinquelineatus, Lutjanus russelli, Lutjanus sebae, Lutjanus vittus, Monacanthus chinensis, Parupeneus barberoides, Plectropomus leopardus, Plectropomus maculatus, Plectropomus pessuliferus (Fowler), *Priacanthus hamrur, Priacanthus tayenus,Psammoperca waigiensis, Rachycentron canadus, Scomberoides commersonianus, Scomberoides tol, Symphorus nematophorus, Uraspis uraspis*

Benthopelagic-piscivorous

Aprion virescens, Galeocerdo cuvier, Glaucosoma magnificum, Rhizoprionodon acutus, Rhizoprionodon oligolinx, Rhizoprionodon taylori, Seriolina nigrofasciata, Sphyrna mokarran

Benthopelagic-planktivorous

Apogon aureus, Apogon brevicaudatus, Apogon cooki, Apogon darnleyensis, Apogon doederleini, Apogon ellioti, Apogon fasciatus, Apogon hartzfeldi, Apogon moluccensis, Apogon nigripinnis, Apogon nigrocincta, Apogon notatus, Apogon poecilopterus, Apogon semilineatus, Apogon septemstriatus, Apogon sp. 2, *Apogon trimaculatus, Centriscus scutatus, Cheilodipterus artus, Cheilodipterus quinquelineatus, Fowleria abocellata, Haliichthys taeniophorus, Hippocampus kuda, Leiognathus elongatus, Leiognathus leuciscus, Leiognathus* sp., *Parapriacanthus ransonneti, Pempheris analis, Rhabdamia gracilis, Selaroides leptolepis, Solenichthys cyanopterus, Trachyrhamphus bicoarctatus*

Pelagic-piscivorous

Chirocentris dorab, Cybiosarda elegans, Echeneis naucrates, Scomberomorus queenslandicus, Scomberomorus semifasciatus, Sphyraena acutipinnis, Sphyraena flavicauda, Sphyraena forsteri, Sphyraena jello, Sphyraena putnamiae

Pelagic-planktivorous

Amblygaster sirm, Anacanthus barbatus, Caesio caerulaureus, Decapterus sp, *Decapterus macrosoma, Decapterus russelli, Dipterygonotus balteatus, Encrasicholina heterolobus, Herklotsichthys lippa,* Hirundichthys sp., *Leptocephalus larva, Pterocaesio chrysozona, Pterocaesio digramma, Rastrelliger kanagurta, Selar boops, Selar crumenophthalmus, Spratelloides gracilus, Stolephorus* sp.

CHAPTER 6

COMPOSITION AND FATE OF DISCARDS

Chapter Authors:
B. Hill, S. Blaber, T. Wassenberg and D. Milton

CONTENTS

6 COMPOSITION AND FATE OF DISCARDS 1

6 COMPOSITION AND FATE OF DISCARDS

The objectives of this part of the study were to

i. Describe and estimate the bycatch composition of the prawn trawl fisheries of the Far Northern Section of the Great Barrier Reef Marine Park.

ii. To establish which species of trawled animals (vertebrates and invertebrates), other than prawns, are returned to the sea alive and dead, and to discover what happens to the dead material.

iii. To determine the importance of trawling discards in the diets of seabirds, their degree of dependence on such discards and the effects of discards on seabird populations.

These objectives were to be achieved as follows:

Composition of discards

- Prawn trawls replicating commercial trawls will be made in the area presently closed to trawling as well as on fishing grounds to the north and south of the area. This trawling will be carried out by QDPI using the FRV Gwendoline May. Approximately 30 trawls will be carried out in each area.
- All material will be identified to the lowest possible taxonomic level.
- Logbook records will be used to quantify the amount of trawling activity in the area and to estimate the amount of bycatch being discarded on the trawl ground.
- In the second and third years bycatch samples are to be collected on a lunar monthly basis to describe the extent and nature of seasonal changes.

Note. Because of curtailment of funding for the project, the seasonal work could not be carried out.

Buoyancy and survival of discards

- Samples of bycatch will be put into tanks of seawater to allow floating and sinking components to be identified.

CSIRO already has information on the survival of many species found in discards, this information will be extended to include species from the study area for which survival information is not available.

Note: Early studies of survival of discards were carried out at sea. Concern about conditions at sea especially the continuous slopping of water in tanks, the vibration from the ship and other disturbances including compromises resulting from the difficulty of keeping large tanks of seawater in the confined space of a trawler, led to recommendations that survival experiments should follow a protocol (Wassenberg and Hill, 1993). This included the duration of experiments and the holding conditions, and especially that survival experiments should be carried out in tanks on land. This was not a practical option in the present study because of the remoteness of the area. At the time the study was planned, there was no information on the composition of discards in the region. Once sampling commenced, we found that fish were the major component followed by crustaceans and molluscs. Previous studies have shown that over 90% of fish captured in trawls are dead when discarded or die shortly afterwards. It was therefore decided that testing survival of fish under the less than satisfactory experimental conditions available would not be done. In the case of invertebrates, two species of portunid crabs made up around 80% of the crustacean catch. Although previous studies had indicated high survival in at least one species of portunid, this was considered an insufficient information base to predict survival of the species caught in the Green Zone region. We therefore decided to carry out survival experiments on the most common of these two species of portunid. The only other invertebrate group, which contributed, significantly to the invertebrate bycatch was bivalves. Previous studies have shown that bivalves are extremely resilient to trawling and it was considered that no useful purpose would be served in carrying out survival experiments on this group.

Identification of surface scavengers

All animals seen feeding on discards from trawlers at the surface will be identified and counts made

Identification of midwater and benthic scavengers

Midwater and benthic scavengers were to be identified and quantified by means of underwater television cameras.

Rates of scavenging measured by the amount of discards removed from set lines

Note: Because of the shallow depths of the trawl grounds in the area (20 to 30m) and known fast sinking speeds for discards, it was decided not to carry out midwater scavenging observations because of the short time that discards spend in this zone. Video observations on the seabed showed very rapid rates of scavenging (most material eaten within 30 mins) and so baited lines were not used.

Effects of discards on the diet of scavengers

Sharks and fish identified as scavengers will be collected from trawls on fishing grounds and their gut contents will be examined to determine the proportion of their diet made up by discards.

Note. Very few large fish were identified as scavengers of discards. Only 17 sharks were collected in trawls and although gut analysis was carried out this is considered to be an insufficient sample for reliable estimation.

Role of discards in the diet of seabirds

Species of seabirds that forage on trawl discards will be identified and their diets studied.

Monitoring of breeding success and population sizes and their changes in response to availability of discards together with the distances travelled by birds to feeding grounds.

Introduction

Since 1980, improvements in navigation aids have enabled trawlers to work closer to the shoals and reefs of the Great Barrier Reef (GBR). This trawling is aimed mainly at red-spot king prawns (*Penaeus longistylus*). Trawling in northern Queensland now has two components: an inshore fishery in the lagoon between the mainland and the reef, targeting tiger prawns (*Penaeus esculentus* and *P. semisulcatus*), and an offshore inter-reef or inter-shoal fishery for *P. longistylus*. Trawlers fishing for prawns catch large amounts of bycatch-animals other than prawns. Some of this bycatch has commercial value and is retained, but most is non-commercial and is dumped overboard; this component is known as discards. Pender and Willing (1989) found that in 1988, prawn trawlers in the Northern Prawn Fishery caught 7 100 t of prawns and over 30 000 t of bycatch.

Commercial trawling is not allowed within the Green Zone and so we carried out a research trawl survey of the Green and areas to the north and south of the Zone in order to determine the composition of prawn trawl bycatch. The results of this survey are described in detail in Chapter 2 of this report but the overall composition will be referred to here. On commercial trawlers, after removal of valuable components such as Moreton Bay bugs, the rest of the catch is dumped over board. Given the large quantities of these discards, its is important to establish what happens to them. Studies in other fisheries have indicated that seabirds may be affected by feeding on this easily accessible food source and so we paid particular attention to the diets and population trends in seabirds in the Far Northern Section of the Marine Park. Other animals also feed on discards, both on the surface and on the seabed and so we identified the scavengers of discards in the Green Zone. The main focus of this section of the work was on in the inter-shoal section of the Green Zone since this the area which is being subjected to increasing fishing pressure and is the least known.

6.1 Description of the discards

6.1.1 Methods

The research vessel used in this study was the Queensland Department of Primary Industries FRV *Gwendoline May*, a 19 m trawler with a 254 kW engine. She was formerly a commercial Queensland east–coast trawler and during the survey was under the command of a former commercial trawler skipper. She deployed two prawn nets (1 pair) through an A-frame at the stern instead of the usual two pairs of nets towed from booms by commercial trawlers. The reasons for this difference were that we did not need large samples and towing over the stern is safer in the offshore section of the Green Zone, which has numerous uncharted reefs. The trawl gear used for collecting samples has been described in Chapter 2.

Samples were collected from 79 trawls of 30 min duration made in the lagoon and a further 43 made in the inter-shoal area (Figure 6.01). These were used for analysis of the composition of the bycatch and the detailed results are reported in Chapter 2. Here we present summary composition data only. All commercially valuable prawns and animals such as Moreton Bay bugs were removed from the catch and the remainder was classified as discards. The discards from each trawl were weighed and a sample (15 to 20 kg) taken at random from the catch. These samples were packaged and frozen on board ship and sent to the CSIRO Cleveland laboratory, where all the animals were identified to the lowest possible taxonomic level and counted. The fish were measured and weighed to give information on the size composition of the fish making up the discards. All information was entered into a CSIRO Oracle database; details on size frequency can be obtained from this source, as they are not presented in this report.

Comparison of bycatch in long and short tows

Our research trawls were of shorter duration than that of commercial trawls. Data collected by the QDPI on the duration of commercial trawls in the areas to the north and south of the Green Zone showed a range from 90 min to 210 min with a mean of 156 min (SD 26.9, n=63). We needed to establish whether the composition of the bycatch from short-duration tows (30 min), used on the research trawler was comparable to that derived from the much longer hauls (around 160 minutes) of commercial trawlers in the region. These long trawls are not necessarily in a straight line because of the islands, reefs and shoals in the region. Two sets of samples were collected on each of two research cruises in the Green Zone, one during May 1992 and the second during March 1995. On each of the sampling cruises, discards were collected from ten short trawls (30 min duration) and ten long trawls (160 to 165 min duration). The 1992 samples were collected in the inshore area, the 1995 samples were collected in the offshore area (Figure 6.01).

We assessed the value of a short (30 min) (in a straight line) tow as a representation of a commercial length (165 min) (not necessarily in a straight line) tow by a prawn otter-trawl in terms of the species composition, catch rates and sizes of fish, from an inshore and an offshore region. Evaluations of this kind have not previously been reported in tropical Australian multi-species fisheries.

Statistical analysis comparing catch rates for short and long tows

The catch rates (kg h-1) of species or species groups (eg. sponges), the total fish catch rate and total invertebrate catch rate were separately compared between tows of 30 and 165 minutes duration separately for inshore and offshore areas. The catch rates for a species or species group for each trawl was standardised to 1 h by multiplying the total weight of that species by a conversion factor. Only those species or species groups that occurred at 6 or more stations were included in this analysis. To stabilise the variance and normalise the data, the catch rate per station was transformed as log10 (catch rate in grams + 10 grams, later converted to kg h-1). Then we fitted a general linear model separately to inshore and offshore stations. The model contained a single factor: tow duration. A term to represent pairs of stations was initially included in the analysis but this term accounted for very little variation and substantially reduced the residual degrees of freedom. Therefore we dropped the term.

Comparison of fish sizes between short and long tows

For each tow, the standard length of the fish was recorded. Only those species or species groups that occurred at 6 or more stations were included in this analysis. We analysed mean fish length per tow in the same way as the catch rates.

To minimise the effect of small samples, only species that were found in at least 11 tows out of a potential 20 tows (10 short, 10 long) were included in this analysis.

The composition of the catch by weight in short and long tows was assessed by principal component analysis, separately for the inshore and offshore areas. The principal component scores for stations were plotted, with different symbols for the short and long tows. The eigenvector coefficients for the species were also plotted, in order to see which species were responsible for "outlier" stations.

The data used for the principal component analysis consisted of a station-by-species matrix where each cell contained the percent of the total catch at that station that had been contributed by that species. Only species that appeared in at least 2 out of 20 stations were included; consequently the row totals were less than 100 (all about 95–99 except one of 80). The data were not standardised further.

6.1.2 Results

Composition of discards

The mean catch rate of fish was similar in the lagoon (17.2 kg per hr in the long tows) and offshore (13.1 kg per hr in the long trawl tows). The invertebrate catch rates for the two areas were very different: 20.7 kg per hour in the long trawl tows in the lagoon and 41.9 kg per hour in long trawl tows in the inter-shoal. Fish were the dominant animals in trawl discards and they formed a slightly higher percentage of the bycatch in the lagoon than in the inter-shoal area (Table 6.01)

Table 6.01 The percentage contribution of various taxonomic groups to discards from 79 trawls in the lagoon and 43 in inter-shoal parts of the Green Zone. Numbers were not available for sponges because many broke up when trawled.

	Lagoon		**Inter-shoal**	
	number	**weight**	**number**	**weight**
All fish	74	72	64	60
All sponges	na	13	na	7
Hard corals	0	0	0	3
All crustaceans	13	7	25	13
Crabs (brachyurans) only	11	5	23	10
All molluscs	12	5	7	4
Bivalves only	11	3	6	1
Cephalopods only	1	1	1	1
All echinoderms	1	1	2	7
Total number or weight analysed	**36289**	**1315 kg**	**13786**	**564 kg**

The main contributors to the invertebrate catch in the lagoon were crustaceans and to a lesser extent molluscs. In the inter-shoal areas, crustaceans were the most abundant invertebrates by number and weight. Some of the taxonomic groups were dominated by particular subgroups. Spatangoid echinoids accounted for 48% of the echinoderms caught in the lagoon whereas crinoids made up 70% of the echinoderms caught in the inter-shoal area. Bivalves made up the majority of the molluscs - 86% of the lagoon and 82% of the inter-shoal molluscs. This trend was also seen at the specific level. Although we caught 99 species of teleosts in the lagoon and 65 in the inter-shoal area, four species made up nearly 39% of the lagoon catch and 36% of the inter-shoal catch by number. In trawls in the lagoon, *Nemipterus furcosus* alone made up 9% of the fish by number (n = 26809) while *Lethrinus genivittatus* made up 18% of the inter-shoal fish (n = 8881). Two species of crabs - *Portunus rubromarginatus* and *P. tenuipes* - made up 77% of the lagoon and 88% of the inter-shoal crustaceans by number.

Fish are clearly the major group in the discards with crustaceans and bivalves the only other significant groups. Fish are also the dominant group in discards from the nearby Torres Strait where they make up between 62 and 90% of the discards (mean 78%) (Harris and Poiner, 1990).

Comparison of catch rates of short and long tows

A total of 141 species was caught in the short (30 min) trawl and 182 in the long (165 min) trawls; of these 108 species were common to both sets. The total number of discard species caught in the short and long trawls was 153; of these, 81 were common to both sets. Of the 59 fish species whose catch rates were analysed in this study, 13 were common to both sets.

Table 6.02 Fish and invertebrate catch rate in short and long trawls
Means, standard deviations and medians for fish catch rates and invertebrate catch rates in short (30 min) and long (165 min) tows both inshore (1992) and offshore (1995) in the far northern Great Barrier Reef.

Location	*n*	**Fish bycatch ($kg\ h^{-1}$)**			**Invertebrate bycatch ($kg\ h^{-1}$)**		
		Mean	**SD**	**Median**	**Mean**	**SD**	**Median**
Inshore							
Short	10	29.99	11.49	29.0	37.98	16.10	36.3
Long	10	17.20	3.07	16.4	20.73	3.24	21.0
Offshore							
Short	10	14.44	9.07	11.75	57.35	73.70	24.1
Long	10	13.12	5.71	13.75	41.99	21.64	36.95

Table 6.03 Estimates of the mean difference in catch rates ($\log_{10}$) of fish and invertebrates between short (30 min) and long (165 min) tows both inshore (1992) and offshore (1995) in the far northern Great Barrier Reef.

	Estimate	**SE**	**df**	***t*–value**	***P***
Inshore					
Fish	0.2148	0.0638	18	3.36	0.0035
Invertebrate	0.2438	0.1106	18	2.20	0.0408
Offshore					
Fish	0.0199	0.1016	18	0.20	0.8469
Invertebrate	–0.2014	0.2324	18	–0.87	0.3974

Overall, catch rates for fish and invertebrate discards varied between short and long tows both inshore and offshore. Inshore, the median catch rates for fish and invertebrates were significantly greater in short duration tows (Tables 6.02 and 6.03). Offshore, the catch rates for fish and invertebrates were not significantly different in short and long tows (Tables 6.02 and 6.03)

The catch rates from short and long tows by the prawn trawler were compared for 101 species of discards that were found in 6 or more tows: 59 fish, 1 sponge, 12 coral, 6 mollusc, 11 crustacean and 12 echinoderm species. Of these, the catch rates for 12 fish, 2 soft corals, 3 crustaceans, 1 molluscan and 1 echinoderm species differed significantly between the short or long tows (Table 6.04).

Table 6.04 Estimate of back transformed mean differences in catch rates of individual bycatch species that were significantly different between short (30 min) and long (165 min) tows (LCL = lower 95% confidence limit, UCL = upper 95% confidence limit; *n* = number h^{-1}, S = short tows, L = long tows, # = not counted)

Species	LCL	Estimate	UCL	df	*n* (S)	*n* (L)	% of total weight
Inshore							
Fish							
Apistus carinatis	1.13	2.1722	4.18	18	216	95	<1.0
Apogon fasciatus	1.49	2.2945	3.53	18	122	45	<1.0
Dactyloptena papilio	0.16	0.3731	0.87	18	24	16	<1.0
Fistularia petimba	1.16	1.9489	3.26	18	92	42	<1.0
Nemipterus furcosus	1.10	1.7681	2.83	18	834	508	6.2
Pseudomonacanthus peroni	0.07	0.2154	0.62	18	90	20	<1.0
Pseudorhombus diplospilus	1.66	3.8353	8.83	18	44	22	<1.0
Pseudorhombus elevatus	1.03	2.6503	6.81	14	18	4	<1.0
Pseudorhombus spinosus	1.59	4.6099	13.33	14	22	24	<1.0
Scolopsis taeniopterus	1.10	1.6642	2.50	18	496	253	2.5
Suggrundus isacanthus	1.62	2.9154	5.25	18	114	41	<1.0
Upeneus tragula	3.48	5.0477	7.32	18	336	70	<1.0
Invertebrates							
Portunus pelagicus	0.06	0.1915	0.57	16	6	17	<1.0
Amusiidae (mixed species)	1.05	2.7052	6.95	18	500	996	<1.0
Offshore							
Invertebrates							
Alcyonaria sp.1	0.04	0.1611	0.69	18	#	#	2.0
Alcyonaria sp.7	0.08	0.1575	0.31	12	#	#	<1.0
Banareia sp.	0.28	0.5093	0.90	16	16	57	<1.0
Crinoid sp.31	0.09	0.1786	0.35	10	#	#	<1.0

Inshore, the fish and invertebrates were more catchable in short-duration tows. Ten fish species out of 49 were caught at higher catch rates in short tows and two in long tows (Table 6.04). More Amusiidae (scallops) were caught in short tows and more crabs (*Portunus pelagicus*) were caught in long tows. Offshore, two alcyonarian, one crustacean (*Banareia* sp.) and one crinoid species also had higher catch rates in long tows.

For all of these species, the confidence limits for the ratio of short haul to long haul catch are quite wide, so interpretation of these results is restricted to concluding which duration is more effective. Many more tows would be needed before the size of the relative efficiency (catch ratio) could be specified with confidence.

While the catch rates for these animals in short or long tows were statistically different, it should be noted that all of these species (except *Nemipterus furcosus*, *Scolopsis taeniopterus* and Alcyonaria sp.1) individually contributed less than 1% and collectively less than 5% to the total weight of either the short or long catches (Table 6.04). These animals therefore would have had little influence on differentiating the catch compositions of the two types of tow. More importantly, the remaining fish species showed no significant difference between short and long tows.

(a) Differences in mean fish sizes in short and long tows

Differences in mean fish sizes between short and long tows

The mean lengths of fish were compared between short and long tows (inshore, 55 species; offshore, 24 species). Only three species (*Apogon ellioti, Leiognathus* sp and *Sorsegona tuberculat*a) were significantly greater in mean length in long tows (Table 6.A.1). No significant difference in mean length between short and long tows was found for any other species.

(b) Catch composition

As shown in Chapter 2, there are clear differences between inshore and offshore habitats in the Green Zone with respect to features such as substrate and composition of the fauna. We also found that these differences extended to the composition of the discards.

Inshore and offshore stations were dominated by fish (Figures 6.02 and 6.03). Stations 1A and 2A were dominated by fish (over 60%) and had no soft coral. Station 7A was dominated by the fish *L. genivittatus*, station 10A had a large component (31%) contributed by two crustacean groups (mixed penaeids and a crab *Portunus rubromarginatus*). The weight of the catch at station 6A was dominated by Alcyonarian sp. 2 (70%).

Principal component analysis of the species composition (percent weight of catch for each species) both inshore (Figure 6.04) and offshore (Figure 6.05) indicated that the catch compositions of short and long tows were relatively homogeneous except for a few outliers in short tows. The stations were spread depending upon the proportion of the catch consisting of fish. Inshore, this proportion ranged from 0.63 (lower) to 0.91 (upper) and offshore from 0.15 (right) to 0.87 (left). The first Principal Component (PC–1) explained about 36% of the variation of the catch composition inshore and 86% of the variation offshore; PC–2 explained 24% of the variation inshore.

At several stations inshore, single items in the catch separated the station from the others and shifted the principal component scores for those stations from the others (Figure 6.04). Two short-haul stations (2A, 4A) each contained a large sponge that contributed 21% and 29% respectively to the total catch weight. The eigenvector coefficients for that species group (Figure 6.06) are on the extreme left. In these cases a high proportion of the catch was invertebrate species. Similarly, about 32% of the catch at stations 3B and 7A consisted of N. furcosus (eigenvector coefficients at Figure 6.06) and 14% of the catch at 6A was made up of mixed penaeid prawns.

6.2 Fate of Discards

The ratio of bycatch to prawns in tropical and subtropical prawn fisheries in Australia is commonly in the range of 5:1 to 10:1 (Harris and Poiner 1990, Hill and Wassenberg 1990, and is retained, almost all—Harris and Poiner estimate around 99% in Torres Strait—is discarded. In order to determine whether the large amount of material that is discarded from prawn trawlers has an environmental impact, we need to know what happens to it once it is dumped. Hill and Wassenberg (1990) examined the fate of discards from prawn trawlers in Torres Strait. They divided discards into floating and sinking components, determined which animals were still alive when discarded, and recorded the scavengers of discards on the surface and on the seabed. The present study followed the same approach except for estimating survival. There is now a considerable amount of information on survival of discards from tropical and subtropical prawn fisheries in Australia. This shows that over 90% of discard fish die, as do cephalopods except for octopods but these are uncommon in the bycatch. Animals that are severely damaged – such as echinoids and soft corals - also have extremely low survival. Robust invertebrates such as bivalves, asteroids, solitary ascidians and most portunid crabs by contrast, have good survival (Wassenberg and Hill, 1989, 1993). Previous studies (see review by Andrew and Pepperell 1992) have shown that survival of trawl discards is affected by two types of factors–external and internal. The main external factors are the duration of the trawl, the amount and type of other discards, and the length of time that the animals are exposed to air on deck before being discarded. Internal factors include the ability of a species to survive trawling, exposure to air and being dumped; the life history stage (juveniles are usually less tolerant than are adults); and the buoyancy of the discarded animals.

Buoyancy is a key factor because animals that are alive when discarded, but float, are vulnerable to surface scavengers and so are likely to have a lower probability of survival. Because of this, we believe the first parameter to measure in determining the fate of discards is buoyancy–whether the animals float or sink. Whether or not they are alive when discarded is important only for those animals that sink. Thus the first step in determining the fate of discards is to partition them into the two components–floating and sinking. The second step is to decide which of the animals that sink are alive when they reach the sea bed. The third step is to identify the scavengers of discards on the surface and on the seabed.

We have not dealt with mid–water scavenging in the present study because previous work suggests that this is a relatively minor process in shallow (10 to 25 m deep) water in Queensland. In general, discards sink rapidly–around 6 m min–1 –and so they spend less time in the water column than the "floaters" spend on the surface or the "sinkers" on the bottom. In Torres Strait, less than 20% of baits suspended in the water column for 10 min after trawls had been hauled, but discarding had not begun, were wholly or partly eaten (Hill and Wassenberg 1990) while in Moreton Bay, in similar experiments, only 2% of baits were eaten (Wassenberg and Hill 1990). Nevertheless, midwater scavenging may have some effect on the fate of discards.

6.2.1 Methods

Buoyancy of discards

Research trawls in the study were routinely of 30 min duration. However, as pointed out above, commercial trawls are around 160 min. To test whether trawl duration might affect the proportion of the discards that either floated or sank, we measured the buoyancy of discards collected from a short-duration trawl representing research trawls and a long-duration trawl representing commercial trawls. We collected samples for these experiments from two parts of the Green Zone–the inshore area and the offshore (reef) area. We used samples collected as described above in the comparison between the catch composition of short and long duration trawls (Section 6.1). Two sets of samples were collected on each of two research cruises in the Green Zone: one during May 1992 and the second during March 1995. On each of the sampling cruises, discards were collected from ten short trawls (30 min duration) and ten long trawls (160 to 165 min duration). The 1992 samples were collected in the inshore area and the 1995 samples in the offshore area (Figure 6.08).

The time when the catch was spilled onto the sorting tray was noted. Large animals (e.g. large sharks and rays) and sea snakes were removed from the catch, noted and discarded. A sample of up to 36 kg was then separated from the catch and from this the prawns and valuable bycatch such as Moreton Bay bugs (Thenus orientalis) were removed and weighed. The remaining material was regarded as discards. These were retained for 20 minutes from the time when the catch was spilled. They were then divided into batches of around 5 kg and each batch was spilled into one of four tanks (670 mm x 400 mm x 680 mm deep) that had been filled to 500 mm depth with seawater. After 5 min the contents were stirred and the floating species were skimmed off and placed into plastic bags for later analysis. The sinking species were then retrieved and also packaged for analysis. All samples were frozen immediately and transported to the CSIRO laboratory at Cleveland where they were thawed, identified to species and counted, and the total weight of each species was recorded. The standard length of fish, disc width of rays and total length of sharks was also measured.

We carried out a mixed model analysis of variance where we treated stratum (inshore or offshore location) and duration of tows as fixed effects and used trawl station within stratum as a random event. This analysis enabled the variation between stations to be removed so that a paired comparison could be made for the short and long tows. Differences between stations were not significant and the variation between stations was pooled with the residual variation in order to increase the degrees of freedom. Only species or species groups sampled at six or more stations were included in this analysis.

Survival of discards

We did not measure survival of discards in this study because of the difficulties of doing these experiments at sea on small vessels in a remote area with rough seas. Such experiments should be carried out in tanks on land where the animals can be maintained in better conditions for at least four days (Wassenberg and Hill 1993). However, there is published information from which we can infer the likely survival from previous studies.

Survival varies considerably between different taxonomic groups; for example, nearly all teleosts, squid and delicate crustaceans are dead when discarded. By contrast, many invertebrates, especially bivalves and crabs, survive being trawled, exposed to air on deck and then discarded (Wassenberg and Hill 1993). Thus the composition of the discards to a large extent decides the proportion of discards that are alive or dead. In Moreton Bay, for example, crabs dominate the catch, teleosts and cephalopods make up a small proportion of the discards (11% on average) and around 80% of discards in Moreton Bay are alive when returned to the sea (Wassenberg and Hill 1990). By contrast in Torres Strait, teleosts averaged 78% and cephalopods 3% of the discards; 98% of these were dead when discarded (Hill and Wassenberg 1990).

Our analysis of discards from the Green Zone showed that in this area, the composition of discards is similar to that of Torres Strait. However, the conditions to which discard animals are exposed in the commercial fishery adjacent to the Green Zone are more stressful than in the Torres Strait study, where 30 min trawl times and a deck exposure of 30 min was used in survival experiments. Commercial trawls in the Northern Great Barrier Reef region are of longer duration—averaging 156 min—with sorting time averaging 45 min. As survival declines with increasing length of trawl and exposure on deck (Wassenberg and Hill 1987), we would not expect survival to be any better than in Torres Strait. Given that only 2% of fish and cephalopod discards survived in Torres Strait, we therefore assumed that nearly all fish from commercial–length trawls in the Northern GBR region are dead when they are returned to the sea. In this region fish make up a large proportion of the discards—around 75% by weight. The only groups with significant survival rates are the crustaceans (mainly the crabs) and the bivalves (which are protected by their heavy shells). In the Green Zone, bivalves made up only 4% of the discards in the research trawls. This left the crabs as being the only group that is returned to the sea with potentially most animals still alive. Portunid crabs made up 85% of the invertebrate discards in the research trawls. One species of portunid, Portunus tenuipes, makes up 53 to 56% of the crustacean bycatch by number, and nearly 10% of the total number of discards. Despite the obvious limitations of doing survival experiments at sea on a small vessel we decided to carry out survival experiments on this species, as there is no previously published information to draw on.

Crabs (Portunus tenuipes) were taken at random from the discards of 30 min duration night–time trawls. Batches of 10 animals were exposed to air for 5, 10, 20 or 40 min before being put into a tank (670 mm x 400 mm x 680 mm deep) containing a 50 mm layer of sand and 500 mm depth of seawater that was continually exchanged. The crabs were checked at the following times after the start of the experiment: 1 h, 6 h, 12 h and thereafter at 24 h intervals until the end of the experiment. Dead crabs were removed and noted. The experiment was terminated after 96 h (4 days), as this has been shown to be an adequate period for assessment of survival of discards from trawling (Wassenberg and Hill 1993).

Benthic and surface scavengers

Surface scavengers

As shown above, a significant proportion of discards float. Previous studies have shown that floating discards are scavenged by a variety of animals (Hill and Wassenberg 1990, Wassenberg and Hill 1990). We attempted to identify these scavengers by means of visual observations using techniques that has been successfully applied in Moreton Bay and Torres Strait (Blaber and Wassenberg 1989, Hill and Wassenberg 1990). Shortly after a trawl shot had been completed, around 5 kg of discards was dumped over board and the number of surface scavengers (birds, dolphins and sharks) attracted to the discards was recorded. Ten–minute observations were made during the day. At night, observations lasted for about 5 min because the floating discards were soon lost in the dark. Even when the ship was stopped, there was always some drift due to wind and currents. Although these times are short, they were adequate for identification in Torres Strait and Moreton Bay where seabirds, sharks and dolphins tended to scavenge close to the trawler, especially when the trawl was hauled. Observations were made in areas open and closed to commercial trawling.

Benthic scavengers

A CCD video camera sensitive to low light levels enclosed in a water-proof housing was used to observe a bait placed on the bottom at night in the offshore region. Lighting was provided by a 100 watt underwater lamp covered by a red filter. The bait—one or two fish 15 to 20 cm in length—was attached to the end of a 90 cm long pole fixed to the frame carrying the camera. We used discard species as bait—most commonly nemipterids and lethrinids (Pentapodus paradiseus and S. leptolepis made up 50% of baits, L. genivittatus 25% and a variety of other species the balance). The bait was on the substrate when the camera frame was on the bottom and it was in the field of view of the camera. The system was left on the bottom for 30 min. Only one observation was made each night and a total of 29 observations were made.

We analysed the recordings by noting the identity and number of scavengers that actually fed on the bait in successive three–minute periods. Because the bait had sometimes been eaten or dispersed before the end of the full 30 min observation period, the total observation time amounted to only 13 h 3 min instead of the 14 h 30 min that the camera spent on the bottom.

6.2.2 Results

There was no overall difference between short–and long-duration trawls with respect to the proportion of discards that floated when both numbers and weights are taken into account (Table 6.05). More animals from 30 min trawls floated compared to animals from 165 min

appears that duration of trawl is not a major factor in determining buoyancy of animals. However, as can be seen from the ranges, there is substantial variation between samples, reflecting the differences in catch composition of individual trawls.

Table 6.05 Summary of the proportion by number and by weight of discards that floated from four different trawl combinations: short and long hauls from inshore or offshore. Data are given as means and range (*n* = 10 trawls in each case). Numbers or weights of animals tested are given in Table 6.21.

Trawl	% by number	% by weight
165 min inshore	34.2 (20.1–56.8)	39.7 (21.8–57.5)
30 min inshore	39.9 (16.2–51.0)	40.6 (20.8–51.8)
165 min offshore	11.1 (8.3–18.3)	8.4 (2.5–18.0)
30 min offshore	15.8 (7.6–29.8)	7.2 (2.2–19.2)

A higher proportion of animals from inshore than offshore trawls floated. When we examine the major taxa in these four categories, we find the same general trends, namely little effect of trawl duration, but a strong difference between inshore and offshore (Table 6.06). Even when the large range is taken into account, ranges from inshore and offshore rarely overlapped.

Table 6.06 The grouped number and weight (kg) of discards by taxon that were tested for buoyancy. Results are from four groups of trawls–inshore and offshore by 30 min and 165 min duration. n = 10 trawls in each case

	Number tested	Percent floating	Weight tested	Percent floating
165 min inshore				
Fish	8400	43	432	44
Crustaceans	965	1	55	1
Echinoderms	556	32	4	23
Cephalopods	152	73	11	78
Others	1402	1	2	2
Total	11475	34	504	40
165 min offshore				
Fish	7800	22	365	24
Crustaceans	4915	1	112	1
Echinoderms	2007	0	35	0
Cephalopods	147	16	10	26
Others	1402	1	645	1
Total	16271	11	1166	8
30 min inshore				
Fish	3058	52	432	44
Crustaceans	332	1	16	1
Echinoderms	152	18	2	15
Cephalopods	20	70	1	76
Others	548	1	20	1
Total	4110	40	471	41
30 min offshore				
Fish	1718	30	72	24
Crustaceans	866	1	21	1
Echinoderms	519	0	8	0
Cephalopods	21	34	3	48
Others	288	3	182	1
Total	3412	16	286	7.2

Around 34% of the discards from long–duration inshore trawls floated (Table 6.06), while only 11% from offshore trawls did so. Around 43% of fish caught by inshore trawls floated when discarded, whereas only 22% of offshore fish floated. As fish make up around three–quarters of the discards (see Table 6.06), they are the main driver in determining the proportion that floats. The same trend was apparent in the cephalopods: 73% of those discarded inshore floated compared to only 16% offshore. Cephalopods, however, form only around 1% of discards and so are a minor contributor to the difference between inshore and offshore: Echinoderms, similarly, are only a minor group in discards, but they also showed a large difference between inshore and offshore—32% of echinoderms from inshore long duration trawls floated, but all those from offshore trawls sank. The echinoderms that floated were mostly spatangoids (heart urchins), which floated because of air trapped in their tests while on deck. No spatangoids were collected offshore. Crustaceans are not buoyant, so floating—which is rare—results from air being trapped in the cephalothorax of damaged animals. Six out of 10 fan-shaped sponges (*Ianthella* sp.) floated when put into water after being left on deck for 15 min. They continued to float for between 30 min and 3 h before sinking. These large, flat sponges have a small stem or holdfast that attaches them to a hard substrate or rock. Sponges that were still attached to rocks sank immediately.

Because of the dominance of fish in floating discards, we compared the buoyancy's of the dominant species from inshore and offshore to clarify the difference between inshore and offshore (Tables 6.07 and 6.08).

As shown in Tables 6.07 and 6.08, only half as many fish discarded from offshore trawls float compared to fish discarded from inshore trawls. This difference comes from two causes—changes in species composition and differences in buoyancy of a few species when caught inshore and offshore.

There are clear differences in species composition between inshore and offshore discards; for example only three species are among the top ten species in the two areas. The top ten species make up 61% of inshore and 85% of offshore fish, and so the buoyancy of these species tends to drive the proportion of discards that float or sink. In inshore waters, the top ten species showed some degree of buoyancy: the lowest was 24%,but in most species over half of the individuals floated. By contrast, three of the ten top offshore species did not float at all and in only one species did more than 50% of the sample float. Fifteen on the top 40 species inshore and 23 offshore, either did not float at all or less than 2% of those tested floated.

Three of the top 40 species showed greater buoyancy when caught in inshore than in offshore waters. In inshore waters 72% of *Nemipterus furcosus* floated whereas offshore only 44% floated; *Paramonacanthus choirocephalus* changed from 44% floating inshore to 16% offshore; *Selaroides leptolepis* changed from 48% to 0%, but the sample was small. Several species showed similar buoyancy inshore and offshore (*Lethrinus genivittatus, Siganus caniliculatus* and *Torquigener pallimaculatus)*, but no species showed greater buoyancy when caught offshore than inshore.

The lower buoyancy of some species captured in the inter-shoal area could be a consequence of the deeper water from which they were captured (mean 35 m) compared to the lagoon (mean 25 m). Harris and Poiner (1990) found that increasing depth could affect buoyancy in some species.

Despite the different results from inshore and offshore trawls, one clear conclusion is that most fish discarded from prawn trawls in the Green Zone sink: around 55% from inshore and nearly 80% from offshore.

Table 6.07 Numbers of fish caught and the numbers that floated after being collected from 10 long–duration trawls (160/165 min) in the inshore "lagoon" part of the Green Zone. A total of 9300 fish of 99 species was captured. This table gives only the top 40 species, which together account for 8869 animals (95.3% of the catch). Percent of catch floating is the product of percent of catch and Percent floating and is the contribution of each species to the overall proportion of the fish discards that float.

Species	Number caught	% of catch	Number floating	% floating	% of catch floating
Nemipterus furcosus	1404	15.0	1016	72	10.8
Lethrinus genivittatus	864	9.3	205	23.8	2.2
Scolopsis taeniopterus	703	7.5	256	36.5	2.7
Priacanthus tayenus	554	6	185	33.4	2
Torquigener pallimaculatus	477	5.1	369	77.4	3.9
Paramonacanthus choirocephalus	427	4.6	186	43.5	2.0
Apogon ellioti	345	3.7	205	59.7	2.2
Leiognathus sp.	314	3.4	143	45.7	1.6
Nemipterus peronii	305	3.3	263	86.2	2.8
Rhynchostracion nasus	271	2.9	155	57.2	1.6
Apistus carinatus	262	2.8	205	78.2	2.2
Saurida undosquama	262	2.8	0	0	0
Eurithmus nudiceps	260	2.8	57	21.9	0.6
Paramonacanthus japonicus	244	2.6	53	21.7	0.6
Upeneus tragula	192	2.1	2	1	0
Engyprosopon grandisquamis	189	2.0	0	0	0
Nemipterus hexodon	145	1.6	46	31.7	0.5
Sorsogona tuberculata	134	1.4	0	0	0
Apogon fasciatus	123	1.3	92	74.8	1.0
Lepidotrigla argus	122	1.3	55	45.1	0.6
Fistularia petimba	116	1.2	78	67	0.8
Suggrundus isacanthus	111	1.2	0	0	0
Lagocephalus scleratus	98	1.0	4	4	0
Synchiropus rameus	88	0.9	0	0	0
Siganus caniliculatus	86	0.9	77	90	0.8
Upeneus sundaicus	72	0.8	0	0	0
Choerodon cephalotes	70	0.8	0	0	0
Dactyloptena papilio	66	0.7	0	0	0
Callionymus grossi	66	0.7	0	0	0
Pseudorhombus spinosis	65	0.7	0	0	0
Choerodon sp.	63	0.7	2	0	0
Pseudorhombus diplospilus	60	0.6	0	0	0
Upeneus asymmetricus	58	0.6	0	0	0
Pseudomonacanthus peroni	57	0.6	53	93	0.6
Caranx bucculentus	42	0.4	0	0	0
Pelates quadrilineatus	37	0.4	30	81	0.3
Upeneus luzonius	35	0.4	0	0	0
Selaroides leptolepis	29	0.3	14	48	0.1
Pentaprion longimanus	27	0.3	18	67	0.2
Gerres oyena	26	0.3	17	63	0.2
Totals	**8869**	**95.3**	**3786**	**42.7**	–

Table 6.08 Numbers of fish caught and the numbers that floated after being collected from 10 long-duration (160/165 min) trawls in the offshore "inter-shoal" part of the Green Zone. A total of 7797 fish of 65 species was captured. This table is restricted to the top 40 species, which together account for 7682 animals (98.5% of the catch).

Species	Number caught	% of catch	Number floating	% floating	% catch floating
Lethrinus genivittatus	1751	22.4	350	20	4.5
Pentapodus paradiseus	1448	18.6	405	28	5.2
Upeneus luzonius	1176	15.1	2	0.2	0.3
Nemipterus furcosus	632	8.1	276	43.7	3.5
Paramonacanthus choirocephalus	557	7.1	91	16.3	1.2
Pristotis jerdoni	271	3.5	134	49.4	1.7
Synodus hoshinonis	226	2.9	0	0	0
Choerodon sp.	174	2.2	0	0	0
Siganus canaliculatus	154	2.0	150	97.4	1.9
Lagocephalus scleratus	132	1.7	0	0	0
Canthigaster compressa	122	1.6	40	32.5	0.5
Torquigener pallimaculatus	117	1.5	84	71.8	1.1
Upeneus tragula	113	1.4	0	0	0
Sorsogona tuberculata	91	1.2	0	0	0
Saurida undosquamis	65	0.8	0	0	0
Pseudorhombus argus	63	0.8	0	0	0
Dasyatis leylandi	56	0.7	0	0	0
Crossorhombus azureus	50	0.6	0	0	0
Cyclichthys jaculiferus	47	0.6	47	100	0.6
Choerodon cephalotes	45	0.6	0	0	0
Trachinocephalus myops	38	0.5	0	0	0
Apogon darnleyensis	37	0.5	0	0	0
Synodus sagenus	37	0.5	0	0	0
Chaetoderma penicilligera	34	0.4	9	26	0.1
Apogon ellioti	30	0.4	17	57	0.2
Pseudorhombus dupliciocellatus	28	0.4	0	0	0
Selaroides leptolepis	26	0.3	0	0	0
Tetrosomus gibbosus	23	0.3	17	78	0.2
Minous trachycephalus	19	0.2	0	0	0
Engyprosopon grandisquama	15	0.2	0	0	0
Syngnathid	12	0.2	0	0	0
Pseudorhombus diplospilus	12	0.2	0	0	0
Apogon brevicaudatus	12	0.2	12	100	0.2
Dactylopus dactylopus	12	0.2	12	100	0.2
Centriscus scutatus	11	0.1	5	45	0
Anchisomus multistriatus	10	0.1	10	100	0.01
Dactyloptena orientalis	9	0.1	0	0	0
Siphamia argyrogaster	9	0.1	0	0	0
Apogon sp.	9	0.1	0	0	0
Pseudochromis quiquedentatus	9	0.1	0	0	0
Totals	**7682**	**98.5**	**1662**	**21.6**	–

Survival of discards

The results of the survival experiment on the crab *Portunus tenuipes* are given in Table 6.09. Survival was high and there was no relationship between the length of time that the crabs were exposed to air on deck and their subsequent survival. If we group the results, the mean survival was 95% ($n = 60$). Even allowing for the longer average sorting time on commercial vessels (45 min), it appears likely that most of the *P. tenuipes* discarded from trawlers survive the process of being trawled and exposed to air.

Table 6.09 Survival of the crab *Portunus tenuipes*
Numbers of crabs that were alive 96 h after being returned to water following exposure to air on deck for various lengths of time. Ten crabs were used in each sample.

Time on deck (min)	Number alive
5	9
5	10
10	10
10	9
20	9
40	10

The survival after discarding has been tested for two other species of portunid. Wassenberg and Hill (1993) found 84% of *Portunus pelagicus* and 98% of *Thalamita sima* survived for seven days after being captured in trawls. However, there may be some longer–term mortality that is not picked up in these relatively short–term experiments. Potter et al. (1991), for example, reported lower returns of tagged *P. pelagicus* that had been collected from trawls than those collected from crab pots; they suggested that mortality from trawling was the cause of the difference.

Scavenging of discards

The daytime observations show that in both the Green Zone and the adjacent zone open to trawling, several species actively scavenged discards on the surface (Table 6.10). The most common scavengers were seabirds, four species of which were seen taking discards. In addition, dolphins and sharks were seen feeding on discards on the surface in the Green Zone, but were not seen in the adjacent areas.

The night–time observations gave a very different result. In a total of 80 observations made at night in the Green Zone (between 2 and 14 observations per night over 21 nights), the only scavengers seen were two dolphins. This difference may be due to the restricted visibility for observers at night. Seabirds and dolphins are easily seen at night when they follow trawlers that are discarding because they approach the vessels and can be seen in the bright decklights (Blaber and Wassenberg 1989, Garthe and Hueppop 1993, Wassenberg and Hill 1990).

Table 6.10 The percentage occurrence of surface scavengers in the Northern Great Barrier Reef region during the day. n refers to the number of observations carried out in that year.

	Green Zone			**General Use Zone**	
	1992	**1993**	**1994**	**1992**	**1993**
Scavenger	$n = 38$	$n = 50$	$n = 20$	$n = 29$	$n = 50$
No scavengers seen	34	32	10	59	30
Crested Tern	55	46	75	21	30
Lesser Frigate	29	34	85	17	20
Greater Frigate	8	6	5	0	2
Brown Booby	8	12	25	10	16
Dolphin	8	2	0	0	2
Shark	5	6	0	0	0
Other Seabirds	10	0	0	0	0

The seabed video camera was deployed 29 times in the offshore part of the Green Zone. On three occasions, no scavengers were attracted to the bait in the 30 min bottom time. In the other 26 observation periods, between one and nine animals (mean 2.6, SD 2.49) were seen to feed on the bait. Most of the scavengers were fish – teleosts or sharks (Table 6.11).

Although sharks and the large teleost *Lutjanus sebae* made up only a small percentage of the scavengers, they usually ate the entire bait, while most of the other scavengers picked at the bait. Nevertheless, crabs and small fish could remove most of the bait in 30 min. These results indicate that discarded fish do not last much more than a few hours at most on the seabed.

Table 6.11 Occurrence of seabed scavengers attracted to a bait on the seabed at night in the Green Zone. The table shows the number of camera drops on which each scavenger was seen and the mean number seen on each occasion when it was present. $n = 29$ camera drops.

Species	**Number of times seen**	**Mean number seen**
Nemipterus furcosus	9	2.0
Pentapodus paradiseus	6	2.5
Lethrinus genivittatus	8	1.3
Lethrinus sp.	2	2.5
Lutjanus sebae	3	1.0
Lutjanus russelli	1	3.0
Sphyraena sp.	1	2.0
Lutjanus vittatus	1	2.0
Saurida sp.	1	1.0
Sharks	8	1.0
Crabs	3	1.3
Squid	1	1.0
Gastropod	1	1.0

6.3 Effects of discards on seabird populations

6.3.1 Methods

The interactions of seabirds and fisheries have been comprehensively investigated in northern temperate waters (e.g. Furness 1984, Montevecchi et al. 1988, Furness et al. 1988, 1992, Garthe & Huppop 1994), in the Benguela region of southern Africa (Abrams 1983, Ryan & Moloney 1988), and in the eastern Pacific and, to a lesser extent, Hawaii (MacCall 1984, Harrison & Seki 1987). These studies found that commercial fisheries may have a variety of direct and indirect effects on seabirds, including influencing their feeding ecology and behaviour, reproductive success and population sizes. However, despite numerous studies of the diets of most tropical seabirds (e.g. Diamond 1984, Harrison et al. 1984, Hulsman et al. 1989, Seki & Harrison 1989, Morris & Chardine 1992), relatively little is known of their relationships with fisheries.

The coupling of food availability with the timing and success of reproduction may be very tight in tropical seabirds (Harris 1977, Nelson 1984, Diamond & Prys-Jones 1986). Hence if food availability changes significantly as a result of trawlers discarding bycatch, fluctuations in population sizes and success of reproduction may relate to changes in commercial fishing effort and location. Demersal trawling for penaeid prawns is the largest and most widespread fishery in tropical Australia (Kailola et al. 1993), including large areas of the Great Barrier Reef. The largest fishery in the region, the Northern Prawn Fishery has a bycatch to prawn ratio of up to 14:1 (Pender et al. 1992). Bycatch from these tropical prawn fisheries is mainly small fish that are discarded and available to scavenging birds (Blaber & Wassenberg 1989, Hill & Wassenberg 1990).

Seabirds are a conspicuous component of the northern Great Barrier Reef which, as a protected area, has a global significance in terms of its large seabird populations and numerous breeding sites (Blaber et al. in press). To examine the possibility that trawling affects seabirds in the Far Northern Great Barrier Reef, a study of its effects was initiated in 1991 as part of the study of the effects of trawling on the far northern Great Barrier Reef.

The objectives of the seabird study reported in this section were to:

1. find out which species of seabirds feed on discards
2. quantify and assess the importance of discards in their diets
3. relate discard feeding to
    a) availability of discards in terms of
        i) species and sizes of discards
        ii) fishing effort, location, and closed fishing seasons
    b) seabird breeding seasons

Study areas

Islands in two areas of the Great Barrier Reef were sampled. The first (Raine Island) is in the Far Northern Section between 11°S and 12°S which includes the Green Zone. The second area is around Lizard Island between 14°36'S and 14°55'S. It is open to trawling between 15 December and 1 March each year. Samples were also obtained from collections made by the Australian Nature Conservation Agency on North-east Herald Cay (16°55'S, 149°20'E) in the Coral Sea, more than 200 km from the nearest trawl grounds.

Species of birds

Diet samples were collected from nine bird species in the far northern section of the Great Barrier Reef; seven species from the Lizard Island area; and five species from North-east Herald Cay (Table 6.12). Altogether 12 species were investigated. Data on breeding seasons were collected as part of a longer-term study of the seabird populations.

Table 6.12 Seabirds from which diet data were obtained from three areas in tropical north-east Australia (FNS = Far Northern Section of Great Barrier Reef; Liz = Lizard Island area; Her = NE Herald Cay; + = samples collected)

Species	FNS	Liz	Her
Sterna bergii (Crested Tern)	+	+	–
Sterna bengalensis (Lesser Crested Tern)	–	+	–
Sterna sumatrana (Black–naped Tern)	+	+	–
Sterna anaetheta (Bridled Tern)	–	+	–
Sterna dougalli (Roseate Tern)	+	–	–
Anous stolidus (Common Noddy)	+	+	–
Hydroprogne caspia (Caspian Tern)	–	+	–
Sula leucogaster (Brown Booby)	+	–	+
Sula dactylatra (Masked Booby)	+	–	+
Sula sula (Red–footed Booby)	+	–	+
Fregata ariel (Least Frigatebird)	+	–	+
Fregata minor (Greater Frigatebird)	–	–	+

Seabird diets

(c) Field sampling

Regurgitated pellets and regurgitated prey were collected from roosting and breeding seabirds in the Green Zone in July 1992; March, April, August, October, November and December 1993; and April 1994. Similar samples were collected from the Lizard Island area in January and August 1992 and in February and June of 1993 and 1994. North-east Herald Cay samples were collected in November/December 1992 and August 1993. Pellets and regurgitated material were either frozen or placed in 70% ethyl alcohol for transport to the laboratory.

(d) Laboratory analyses

Fish prey items in pellets were identified from otoliths by comparing them to a reference collection. This collection was also used to construct otolith weight to fish length (standard length) regressions in order to back-calculate fish lengths. Cephalopoda were identified as far as possible from beaks or shells. Whole regurgitated prey were identified, measured and weighed. Diets were analysed in terms of the numerical frequency of each prey taxon.

Identification of benthic prey and prawn trawl discards in the study areas

In the Far Northern Section, discards from the research trawler Gwendoline May were collected as part of the overall "Effects of Fishing" project (Wassenberg et al. in press). This included a very large number of fishes (>50,000) in samples from 69 stations in May 1992 and 79 stations in March 1993 from both the closed area and the adjacent area open to trawling. The Gwendoline May used standard commercial Florida Flyer prawn trawls. These trawls are demersal and the discards consist almost entirely of benthic species not normally available to seabirds.

In the Lizard Island area information on the composition of discards was obtained from 26 stations trawled by the "Gwendoline May" during a research cruise in June 1993. All discard samples were frozen on board the vessel and taken to the laboratory for sorting, identifying and measuring. Discard species were classified as benthic (following Blaber et al. 1990) and either "floating" or "sinking" (following Harris & Poiner 1990). The composition of discards in trawled and untrawled areas and between seasons and sites were compared by Spearman's Rank Correlations.

Prawn trawling effort and location in the study areas

The prawn catch can be used as a guide to the amount of discards. Prawns usually represent 10–20% of the catch. The remaining 80–90% is bycatch, mainly fish, which is discarded (Pender et al. 1992). Data on the number of trawlers and the number of days they spent trawling in the study areas were extracted from the "QFISH" database, which is maintained jointly by the Queensland Department of Primary Industries and Queensland Fish Management Authority. It is compulsory for all trawlers to supply these authorities with logbook data.

Table 6.13 Diets of *Sterna bergii* (Crested Tern). Data from the Lizard Island section of the Great Barrier Reef during closed and open trawl seasons (data combined for 3 samples in each season) and in the Far Northern Section in the zone closed to trawling (data combined from 5 samples) and in adjacent zones open to trawling (data combined from 3 samples) expressed as percentages of the number of food items eaten (%) (* = benthic taxa)

Site	**Lizard Island area**		**Far Northern section**	
Prey taxa	**Closed season**	**Open season**	**Closed zone**	**Trawl ground**
Agamid lizard	–	0.6	–	–
*Alphaeidae	–	–	–	0.9
Amblygaster sirm	87.5	–	0.6	–
**Anchisomus multistriatus*	<0.1	–	–	–
*Apogonidae	1.0	39.2	5.2	25.5
Atherinomorus lacunosus	3.7	4.0	20.6	0.9
Beloniformes	0.6	–	–	–
*Blenniidae	0.1	–	–	–
*Brachyura	0.4	0.6	0.6	0.9
**Callianassa* sp.	–	–	28.4	–
Caranx sp.	0.6	–	0.6	–
**Choerodon* sp.	0.2	–	1.9	7.5
Clupeidae	0.2	–	–	0.9
*Gerreidae	–	3.4	–	–
*Gobiidae	0.2	30.7	22.6	18.9
Green turtle hatchlings	–	–	2.6	–
Halichoeres sp.	<0.1	–	0.1	–
Hemiramphidae	–	–	–	1.9
Herklotsichthys quadrimaculatus	0.2	–	0.6	–
Isopoda	–	–	–	0.9
Megalaspis cordyla	0.1	–	–	–
**Metapenaeus endeavouri*	0.1	–	–	0.9
Mulloides sp.	0.1	–	–	–
**Nemipterus* sp.	0.1	1.1	–	–
Paraexocoetus sp.	0.1	–	–	–
**Penaeus latisulcatus*	–	1.1	0.6	0.9
**Penaeus plebejus*	–	–	–	1.9
*Pomacentridae	1.6	9.7	–	–
**Pristotis jerdoni*	0.8	–	–	–
**Pseudochromis* sp.	<0.1	–	–	–
Scombridae	0.1	–	–	–
Sepia sp.	0.5	–	–	–
**Sillago* sp.	–	–	–	8.5
Spratelloides sp.	0.2	1.1	0.6	–
Stethojulis strigiventer	0.2	–	–	–
Sthenoteuthis sp.	0.1	–	–	1.9
*Terapontidae	–	0.6	–	–
Teuthoidea	0.2	1.1	3.9	–
unidentified cephalopods	0.7	–	–	–
unidentified teleosts	0.4	6.3	9.7	26.4
Total number of prey	**1037**	**176**	**155**	**106**

Table 6.14 Length ranges of prey of terns from Lizard Island and Far Northern areas (Sb = Sterna bergii, Sbg = S. bengalensis, Ss = S. sumatrana, Sa = Sterna anaetheta, Sd = S. dougalli, As = Anous stolidus, Hc = Hydroprogne caspia)

Prey Predator	*Sb*	*Sbg*	*Ss*	*Sa*	*Sd*	*As*	*Hc*
Amblygaster sirm	32–121	–	61–81	24–110	–	–	–
Apogonidae	33–108	74	33–41	30–49	–	33–42	60
Atherinomorus lacunosus	23–102	43–74	19–66	22–82	25–58	23–71	61–87
Blenniidae	–	–	–	12	–	–	–
Caranx sp.	52–98	–	–	–	–	–	–
Encrasicholina spp.	–	–	20–34	25–35	35–46	–	–
Gerreidae	64–75	–	–	–	–	–	–
Gnathanodon speciosus	–	–	–	13	–	–	–
Halichoeres sp.	103	–	–	–	–	–	–
Herklotsichthys quadrimaculatus	41–85	–	12–30	24	18–22	11–33	–
Lagocephalus lunaris	–	–	–	18–19	–	–	–
Lutjanus spp.	–	–	–	–	–	–	250
Megalaspis cordyla	110	–	–	–	–	–	–
Monacanthidae	–	–	–	17–19	–	–	–
Mulloides sp.	–	–	–	32–48	–	55–58	–
Myripristis sp.	–	–	–	49	–	–	–
Paraexocoetus sp.	84	–	–	–	–	–	–
Pomacentridae	20–64	–	10–58	6–89	–	13–43	39
Priacanthus sp.	–	–	–	11–13	–	–	–
Pristotis jerdoni	43–55	–	–	39–41	–	–	–
Pseudochromis sp.	65	–	–	–	–	–	–
Sepia sp.	34–90	–	–	31	–	–	–
Sillago sp.	78–138	–	–	–	–	–	–
Spratelloides sp.	9–24	18	–	10–55	8–13	8–31	–
Stethojulis strigiventer	48–66	–	–	44	–	–	–
Sthenoteuthis sp.	–	–	–	–	–	–	–
Teuthoidea	91	–	–	–	–	–	–
Upeneus tragula	–	–	–	23–35	–	53–58	–
Xiphasia spp.	–	–	–	48	–	–	–
Overall length range	9–138	18–74	8–81	6–110	8–58	11–71	39–250

6.3.2 Results

Diets from the Northern Great Barrier Reef region

The proportions of benthic and pelagic prey for each species are shown in Figure 6.09.

***Sterna bergii* (Crested Tern)**

A total of 755 regurgitated pellets and 462 regurgitated whole fish samples were used in the analysis. In the Lizard Island area the diet of S. bergii changed markedly between closed and open trawling seasons (Table 6.13). During the closed season the prey consisted mainly of pelagic species such as *Amblygaster sirm* and *Atherinomorus lacunosus*, whereas in the trawling season it consisted mainly of benthic groups such as *Apogonidae* and Gobiidae. The benthic prey are from taxa characteristic of prawn trawler discards (Table 6.13). They include the penaeid prawns *Metapenaeus endeavouri* and *Penaeus latisulcatus*–the benthic target organisms of the fishery–small numbers of which are discarded if broken or damaged. The length ranges of pelagic and benthic prey were similar (Table 6.14) and were within the size range of fishes discarded by trawlers.

All the diet samples from the Far Northern Section were collected during the trawling season. Nevertheless, in both the zone open to fishing and the zone closed to fishing, the diet consisted predominantly of benthic species characteristic of trawl discards (Table 6.13), including several species of penaeid prawns. Only in the closed zone in November 1993 were more pelagic prey (*A. lacunosus*; 70% of numbers) than benthic prey eaten.

***Sterna bengalensis* (Lesser-crested Tern)**

Diet samples were only available from the Lizard Island area in the closed season. In the 39 regurgitated pellets, the prey consisted mainly of pelagic species, although some benthic trawl discard species were recorded (Table 6.14, Figure 6.09). The longest prey was shorter than in *S. bergii*'s diet (Table 6.13).

***Sterna dougallii* (Roseate Tern)**

Only 16 regurgitated pellets were collected, all from the Far Northern Section from Sir Charles Hardy (detached portion of closed zone) and Sunday Islands (14 in Figure 6.10, open zone). In the zone closed to trawling half the prey were pelagic, the remainder were Gobiidae; in the Green Zone it was all pelagic (Table 6.15). The overall proportions of benthic and pelagic prey are shown in Figure 6.09. The longest prey (58 mm) was shorter than the largest prey eaten by any of the other tern species studied. The prey were within the length ranges discarded by trawlers.

Table 6.15 Diets of Lesser-Crested Terns, Roseate Terns, Caspian Terns in the Northern Great Barrier Reef region. Expressed as percentages of the number of food items eaten (%) (*Sbg*= *S. bengalensis*, *Sd* = *S. dougalli*, *Hc* = *H. caspia*, *Sa* = *S. anaetheta*;* = benthic taxa)

Species	***Sbg***	***Sd***	***Sd***	***Hc***	***Sa***
Site	**Lizard closed season**	**FNS closed zone**	**FNS trawl ground**	**Lizard open season**	**Lizard closed season**
Date	**Feb 1994**	**Jul 1992**	**Jul 1992**	**combined**	**combined**
Prey taxa					
*Alpheidae	–	–	–	2.9	–
Amblygaster sirm					24.4
*Apogonidae	6.2	–	–	2.9	19.9
Arramphus sp.	–	–	10.0	–	–
Atherinomorus lacunosus	43.9	37.5	–	11.8	8.6
Blenniidae	–	–	–	–	0.4
**Choerodon* sp.	12.5	–	–	–	
Clupeidae	–	–	–	–	1.5
Encrasicholina sp.	–	–	90.0	–	6.4
Exocoetidae	–	–	–	17.6	0.4
Gnathanodon speciosus	–	–	–	–	0.4
*Gobiidae	–	53.6	–	–	1.1
Herklotsichthys quadrimaculatus	–	5.3	–	–	0.4
Lagocephalus lunaris	–	–	–	–	0.8
*Lutjanidae	–	–	–	2.9	–
Monacanthidae	–	–	–	–	0.8
Mulloides sp.	–	–	–	–	1.5
**Myripristis* sp.	–	–	–	–	0.4
*Penaeidae	–	–	–	2.9	–
*Pomacentridae	–	–	–	2.9	8.6
**Priacanthus* sp	–	–	–	–	1.5
**Pristotis jerdoni*	–	–	–	–	0.8
Spratelloides sp.	12.5	3.6	–	–	2.7
Stethojulis strigiventer	–	–	–	–	0.4
**Upeneus tragula*	–	–	–	–	4.1
Xiphasia matsubaria	–	–	–	–	0.4
Cephalopoda (unidentified)	18.7	–	–	–	1.2
Teleostei (unidentified)	6.2	–	–	55.9	10.2
Total prey (*n*)	**16**	**56**	**10**	**34**	**266**

Table 6.167 Diets of Common Noddies and Black-Naped Terns in the Northern Great Barrier Reef region Expressed as percentages of the number of food items eaten (%) (* = benthic taxa)

Bird species	*Anous stolidus*			*Sterna sumatrana*			
Prey taxa	**Lizard Island area**		**Far North**	**Lizard Island area**		**Far North**	
	Closed season	**Open season**	**Trawl ground**	**Closed season**	**Open season**	**Closed zone**	**Trawl ground**
Amblygaster sirm	–	–	–	0.5	–	–	
*Apogonidae	0.6	6.8	–	1.6	0.6	–	–
Atherinomorus lacunosus	54.4	14.1	11.4	59.5	77.0	80.0	36.9
**Choerodon* spp	–	<0.1	–	–	–	–	–
Clupeidae	–	1.3	–	2.4	–	–	–
Encrasicholina sp.	–	0.6	–	7.9	–	–	–
*Gobiidae	–	0.3	–	–	–	–	–
Herklotsichthys quadrimaculatus	33.7	39.3	82.9	17.9	18.2	16.9	59.5
*Pomacentridae	1.0	0.1	–	5.0	–	–	–
Spratelloides gracilis	–	0.1	–	–	–	–	–
Spratelloides sp.	2.8	21.9	5.7	–	3.7	4.1	2.4
Teuthoidea	0.2	–	–	–	–	–	–
**Upeneus tragula*	1.2	–	–	–	–	–	–
Mullidae	–	0.1	–	–	–	–	–
unidentified teleosts	6.1	1.3	–	1.1	0.4	–	1.2
Total number of prey	**507**	**1569**	**35**	**380**	**488**	**59**	**84**

Hydroprogne caspia (Caspian Tern)

In all 98 regurgitated pellets were obtained from the Lizard Island area, all in the trawling season. Although much of the prey was unidentifiable, most of those that could be identified were pelagic (Table 6.15, Figure 6.09). The longest prey recorded (250 mm) was greater than, in the diet of other terns (Table 6.14).

Sterna anaetheta (Bridled Tern)

Samples were collected during closed fishing seasons from the Lizard Island area. A total of 117 regurgitated pellets and 43 regurgitated whole-prey samples was obtained. The diet was dominated by pelagic species (Table 6.14) except in February 1994 when the quantities of Apogonids were significant.

Sterna sumatrana (Black-naped Tern)

Data from 237 regurgitated pellets collected from the Lizard Island area in both open and closed trawl seasons, and from the trawl grounds and closed zone of the Far Northern Section, show that this species feeds almost exclusively on small pelagic clupeids, engraulids and atherinids (Table 6.13, Figure 6.09).

Anous stolidus (Common Noddy)

A total of 412 regurgitated pellets and 155 regurgitated whole-fish samples was collected. In the Lizard Island area in both open and closed seasons the birds were eating mainly small pelagic species, and small quantities of species from the benthic trawl bycatch. No benthic prey items were recorded from the Far Northern Section (Table 6.16, Figure 6.09).

Sula leucogaster (Brown Booby)

In the closed zone, 11 regurgitated pellets and 79 regurgitated prey samples were collected from Raine Island; in the trawl grounds, 18 regurgitated prey samples were collected from Sandbanks numbers 7 and 8. The diet was very diverse but consisted mainly of pelagic prey (Table 6.17, Figure 6.09). Small quantities of benthic trawl bycatch taxa were recorded from both the open and closed zones. They included Apogonidae, *Kyphosus* sp., *Lethrinus* sp. and Terapontidae, as well as bivalves.

Sula dactylatra (Masked Booby) and Sula sula (Red-footed Booby)

Regurgitated prey samples were collected from Raine Island in the closed zone: 81 from *S. dactylatra* and 36 from *S. sula*. The diets of both species consisted entirely of pelagic prey, but whereas *S. dactylatra* had eaten mainly flying fishes and a few squid, *S.sula* had eaten mainly squid with only a few flying fishes (Table 6.18, Figure 6.09).

Table 6.17 Diets of Brown Boobies from the Northern Great Barrier Reef region (July 1992, Mar 1993, Dec 1993 combined) and adjacent trawl grounds (April 1992) of the Far Northern Section of the Great Barrier Reef expressed as percentages of the number of food items eaten (%) (* = benthic taxa, ml = mantle length). The length ranges (SL mm) of prey are also shown.

Prey taxa	Closed zone	Trawl grounds	Length range
Amblygaster sirm	2.0	–	115–195
*Apogonidae	9.3	–	26–98
*Bivalvia	–	0.4	–
Caesio caerulaurea	–	1.6	92–149
Coryphaena hypura	–	0.8	94–101
Decapterus russelli	0.3	4.8	40–110
Euleptorhamphus viridis	0.3	–	203
Exocoetidae (7 taxa)	8.0	8.0	49–256
Green turtle hatchlings	3.9	–	38–54
Halichoeres sp.	0.3	–	79
Hyporhamphus affinis	–	5.2	87–250
**Kyphosus* sp.	0.3	–	78
**Lethrinus* sp.	0.3	–	140
Megalaspis cordyla	0.3	–	115
Mulloides sp.	26.2	28.7	38–59
*Pomacentridae	–	0.8	26–52
Psenes sp.	–	1.2	92–105
Scomberoides sp.	0.6	–	80
Scomberomorous sp.	0.3	–	79
Scombridae	0.3	–	170
Selar sp.	0.3	–	100
Sepia sp.	0.3	–	95 (ml)
Seriola sp.	–	1.2	38–64
Spratelloides delicatulus	25.1	–	25–55
Sthenoteuthis sp.	14.1	38.2	26–185 (ml)
**Terapon jarbua*	–	2.8	48–90
Teuthoidea	7.3	–	28–212 (ml)
unidentified teleosts	0.6	6.1	29–200
Total number of prey	**355**	**251**	

Table 6.18 Diets of Masked Boobies and Red-Footed Boobies in the Northern Great Barrier Reef region December 1993; expressed as percentages of the number of food items eaten (%). The length ranges (mm SL) of prey are given

Prey taxa	*S. dactylatra*	mm SL	*Sula sula*	mm SL
Beloniformes	1.3	200	–	–
Caesio caerulaurea	1.3	200	–	–
Cheilopogon sp.	2.6	199–205	2.3	153
Cypselurus sp.	15.8	162–260	11.4	127–190
Decapterus russelli	–	–	6.8	50–59
Exocoetidae	40.8	100–240	13.6	35–170
Exocoetus volitans	2.6	176–180	–	–
Fodiator sp.	1.3	147	–	–
Hirundichthys sp.	23.7	145–225	–	–
Paraexocoetus sp.	1.3	135	–	–
Prognichthys sp.	1.3	166	–	–
Scombridae	1.3	200	–	–
Sthenoteuthis sp.	6.7	57–80	54.6	30–85
Teuthoidea	–	–	4.5	50–55
Unidentified teleost	–	–	6.8	50–60
Total number of prey	**76**		**44**	
Overall length ranges		**57-260**		**30–190**

Fregata ariel (Least Frigatebird)

The data from 88 regurgitated prey samples from Raine Island suggest this species feeds on a wide variety of pelagic prey in the closed zone of the Far Northern Section. Small numbers of benthic trawl bycatch taxa, such as lethrinids and leiognathids were, however, recorded in both March and December 1993 (Table 6.19, Figure 6.09).

Table 6.19 Diets of Least Frigatebirds in the Northern Great Barrier Reef region March and December 1993; expressed as percentages of the number of food items eaten (%). The prey length ranges (mm SL) are given (* = benthic taxa).

Prey taxa	Mar 1993	mm SL	Dec 1993	mm SL
Alepes sp.	1.3	100	–	–
Amblygaster sirm	–	–	1.0	170–184
Argyropelecus sp.	10.5	50–90	5.0	45–80
Beloniformes	–	–	0.4	160
Carangidae	6.6	85–115	–	–
Cheilopogon sp.	6.6	60–101	–	–
Clupeidae	1.3	95	–	–
Cypselurus sp.	–	–	0.4	190
Decapterus russelli	–	–	0.4	65
Encrasicholina sp.	18.4	28–36	–	–
Exocoetidae	9.2	100–150	6.5	114–220
**Gerres oyena*	2.6	112–120	–	–
Gymnocaesio gymnoptera	2.6	113–130	–	–
Hirundichthys sp.	2.6	155–180	2.5	170–196
*Labridae	–	–	0.4	115
*Leiognathidae	1.3	90	0.4	90
**Lethrinus* sp.	1.3	90	–	–
**Lethrinus nematacanthus*	4.0	83–115	–	–
**Nemipterus* sp.	–	–	1.0	120–160
Paramonacanthus sp.	–	–	2.2	24–33
Pentapodus paradiseus	1.3	125	1.5	130–160
Rhabdamia sp.	–	–	0.4	20
Scombridae	5.3	100–140	0.7	54–121
Selar sp.	2.6	80–135	0.4	164
Selaroides leptolepis	–	–	7.3	95–142
Sepia sp.	–	–	0.4	100
*Sillaginidae	4.0	100–120	–	–
Sthenoteuthis sp	2.6	37–42	41.1	22–102
Teuthoidea	15.8	40–105	21.5	30–90
**Upeneus luzonius*	1.3	95	–	–
Unidentified teleosts	–	–	6.5	50–170
Total number of prey	**76**		**275**	
Overall length ranges		**28–180**		**20–220**

Diets from the Coral Sea

The food of three Sulidae and two Fregatidae, identified from samples collected on North-east Herald Island, consisted predominantly of at least four species of flying fishes (Exocoetidae) and the pelagic squid *Sthenoteuthis* sp. There were also smaller numbers of other pelagic fishes such as *Auxis* (tuna), *Coryphaena* (dolphin fish) and *Encrasicholina* (anchovy) (Table 6.20). No benthic prey was recorded. Although the five bird species ate much the same species, they ate them in different proportions. *S. dactylatra* and *F. minor* ate >50% flying fish whereas the other species took <20%. *S. sula*, *F. ariel* and *F. minor* ate >30% squid while *S. leucogaster* and *S. sula* were the only species to eat engraulids.

Prawn-trawl discards

The taxonomic composition of the bycatch discarded by prawn trawlers in each study area is listed in Table 6.21. Only taxa found in seabird diets are shown. They make up approximately half the total numbers of organisms discarded, and most float after being discarded (Harris and

Poiner, 1990). The composition of discards was similar at both study sites, with significant rank order correlations regardless of time of year (Spearmans *rho* 0.7, $p<0.01$). The composition of discards was similar in the area open to commercial trawling and the closed area. (Spearmans *rho* 0.86, $p<0.001$ for March, 0.81, $p<0.001$ for May).

The Sulidae and Fregatidae ate a wide range of sizes of prey, but none of the terns, except *Hydroprogne caspia* could apparently do so (Table 6.14). As shown below, Crested Terns and Brown Boobies prefer prey smaller than around 120mm

The overall proportions of benthic trawl bycatch prey and pelagic prey are shown for each species in Figure 6.09. The species whose diets consist of at least 20% discard taxa are *S. bergii, S dougallii* and perhaps *S. anaetheta*; those with between 5 and 19% are *H. caspia, A. stolidus, S. bengalensis, S. leucogaster* and *F. ariel*; those <5% are *S. sumatrana*; and none, *S. dactylatra* and *S. sula.* This categorisation is not rigid, however, as considerable variations within species were recorded, both in relation to open and closed fishing seasons and open and closed zones.

Prawn-trawling effort and seabird breeding in the study areas

The greatest number of trawling days per month were in March of each year, which is immediately after the opening of the trawling season (Figures 6.11 & 6.12). The bycatch would also have been at its greatest at this time. Around Lizard Island catches became smaller as the year progressed, but discards would have been available throughout the season, until it ended in mid-December (Figure 6.12). In the southern part of the Far Northern Section the pattern was similar, but north of the closed zone, catches were more evenly spread through the fishing season (Figure 6.11).

The breeding times for each bird species in the two areas are also shown in Figures 6.11 and 6.12. Around Lizard Island *S. bergii, S. bengalensis, S. anaetheta* and *S. sumatrana* all nested and raised young in the closed fishing season (CSIRO unpublished records), whereas *H. caspia* nested in June and July (Figure 6.12). In the Far Northern Section most species likewise showed peak breeding activity from November to February, but some *S. bergii, S. anaetheta* and *A. stolidus* also nested in June and July (CSIRO and QDEH unpublished records) (Figure 6.11).

Table 6.20 Diets of seabirds from North-east Herald Island. Analysed from material collected in November 1992 and August 1993. (Sl = Sula leucogaster; Sd. = Sula dactylatra; Ss = Sula sula; Fm = Fregata minor; Fa = Fregata ariel). Length ranges (mm SL) of prey are given.

Bird species **Prey taxa (% numbers)**	***Sl* Nov 92**	***Sl* Aug 93**	**mm SL**	***Sd* Nov 92**	***Sd* Aug 93**	**mm SL**	***Ss* Nov 92**	***Ss* Aug 93**	**mm SL**	***Fm* Nov 92**	***Fm* Aug 93**	**mm SL**	***Fa* Nov 92**	***Fa* Nov 93**	**mm SL**
Auxis sp.	3.4	–	150–195	–	12.0	200–290	–	–	–	–	–		–	–	–
Beloniformes	–	–	–	–	4.0	200	–	0.9	96	–	–	–	–	50.0	51
Cheilopogon spp.	–	–	–	16.2	20.0	194–315	–	–	–	–	–	–	–	–	–
Clupeidae	1.7	–	73	–	–	–	–	–	–	–	–	–	–	–	–
Carangidae	6.8	–	80–195	–	–	–	–	–	–	–	–	–	–	50.0	43
Coryphaena sp.	–	–	–	2.3	–	133	–	–	–	–	–	–	–	–	–
Cypselurus spp.	–	–	–	–	12.0	108–149	–	–	–	–	–	–	–	–	–
Decapterus sp.	5.1	–	85–134	2.3	–	123	3.3	–	110–180	–	–	–	–	–	–
Encrasicholina heteroloba	–	92.5	20–37	–	–	–	34.4	6.9	18–69	–	–	–	–	–	–
Exocoetidae	35.6	–	50–240	37.2	8.0	80–261	24.4	0.9	66–190	5.9	100.	120–170	18.2	–	–
Hemiramphidae	1.7	1.9	75–260	–	–	–	–	–	–	–	–	–	–	–	–
Hirundichthys spp.	–	–	–	16.2	4.0	85–214	–	0.9	130	–	–	–	–	–	–
Hyporhamphus quoyi	–	–	–	–	–	–	6.7	–	60–120	–	–	–	–	–	–
Katsuwonus pelamis	11.9	–	70–185	18.6	–	140–225	8.9	–	84–165	17.6	–	130–146	–	–	–
Pampus spp.	–	–	–	–	–	–	–	1.7	25–30	–	–	–	–	–	–
Paraexocoetus spp.	–	0.6	137	–	–	–	–	–	–	–	–	–	–	–	–
Seriolina sp.	–	–	–	–	–	–	–	–	–	–	–	–	2.3	–	150
Sthenoteuthis spp.	15.2	4.4	23–101	7.0	28.0	51–100	22.2	69.8	20–100	70.6	–	59–100	79.5	–	40–104
Teleostei	5.1	0.6	29–224	–	12.0	60–100	–	0.9	–	5.9	–	170	–	–	–
Xiphasia matsubarai	3.4	–	300–370	–	–	–	–	–	–	–	–	–	–	–	–
Xiphasia setifer	10.2	–	120–270	–	–	–	–	18.0	50–150	–	–	–	–	–	–
Total number of prey	**59**	**160**		**36**	**25**		**90**	**116**		**17**	**4**		**44**	**2**	
Overall length ranges			**20–370**			**51–315**			**18–190**			**59–170**			**40–150**

Table 6.21 Trawl discards that were found in diets of seabirds from the sample sites. Expressed in terms of the percentage contribution of each taxon (by numbers) to the total number of discards. Also shown for each taxon are whether the discards float or sink (F, S) and their length range (standard length) (cm SL) for each site and time (- = no data).

Discard		**Turtle Is.**		**Far Northern Great Barrier Reef**							
Prey taxa	**F/S**	**June 1993**	**cm SL**	**May 1992 trawl area**	**cm SL**	**May 1992 closed**	**cm SL**	**Mar 93 trawl area**	**cm SL**	**Mar 93 closed**	**cm SL**
Apogonidae	F	5.4	2-11	3.4	5-7	3.1	3-15	5.7	3-10	7.0	3-11
Cephalopoda	F	2.0	-	1.0	-	0.9	-	1.1	-	1.0	-
Choerodon spp.	-	1.8	-	2.1	8-14	1.1	7-13	1.3	7-14	0.9	7-14
Decapterus spp.	F	-	9-16	0.1	10-20	<0.1	6-16	0.1	18-22	<0.1	11-20
Gerreidae	F	0.3	5-15	0.2	10-14	1.1	8-14	0.3	13	0.3	8-14
Gobiidae	F/S	0.1	6-12	0.2	9-13	0.2	8-13	0.2	11-13	0.2	10-14
Leiognathidae	F	0.1	6-11	0.4	6-12	0.4	3-12	0.6	6	1.4	8-12
Lethrinus genivittatus	F	26.0	3-16	12.9	8-17	10.9	9-17	8.1	3-17	7.6	9-17
Pentapodus spp.	F	5.3	5-20	3.2	6-22	1.2	5-23	2.8	7-20	1.8	9-21
Pomacentridae	F	1.2	3-9	0.1	5-8	0.6	6-9	1.1	5-10	2.0	5-10
Selar spp.	S	-	9-16	0.1	13-18	<0.1	6-16	<0.1	13-21	<0.1	11-20
Sillago spp.	F	0.5	12-20	0.7	13-18	1.2	11-17	0.4	13-19	0.2	15-19
Terapontidae	F	0.5	5-11	0.1	11-14	3.4	9-15	0.8	-	0.1	-
Mullidae	S	8.4	4-16	5.7	8-17	9.3	-	5.4	6-16	6.0	5-23
Monacanthidae	F	3.5	2-16	4.6	7-19	3.5	7-21	10.2	7-23	8.7	4-36
Priacanthus sp.	F	0.2	8-21	1.2	12-20	1.5	4-22	0.5	8	<0.1	8-23
Tetraodontidae	F/S	0.9	5-15	2.1	6-16	2.8	4-46	3.6	4-32	1.3	5-29
Invertebrata											
Penaeidae	S	0.2		0.07		0.2		0.		0.03	
Squid	F/S	0.2		0.07		0.07		0.3		0.55	
Sepia spp.	F	1.6		0.9		0.77		0.7		0.58	
Bivalvia	S	0.1		8.6		4.9		5.4		9.8	
Alpheidae	S	0		<0.1		<0.1		0		<0.1	
Total percentages		**61.8**		**47.8**		**44.3**		**48.7**		**49.9**	
Number of species		**155**		**128**		**145**		**282**		**184**	

6.4 Seabird populations of the Far Northern Great Barrier Reef, Australia, with particular reference to effects of trawling

The second objective of the study was to assess whether trawling affects the sizes or distributions of seabird populations.

6.4.1 Methods

The study area was the same as for the study of discards in bird diets: from 9°00' S to 16°00' S, encompassing both the Lizard Island area between about 14° and 15°S and the Green Zone area.

Records from 1977 to the present were obtained from the databases of the Royal Australasian Ornithologists Union, from records of regular surveys made by the Queensland National Parks and Wildlife Service, from a number of independent observers, from the scientific literature, and from surveys made by CSIRO project staff between 1991 and 1995. All bird counts were entered into a common format in an Oracle database. A 'count' was defined for this study as the number of individuals of one species at one site (usually an island) on a single date.

The overall number of counts per month was relatively evenly distributed, with the exception of September (Table 6.22). However, the geographic spread of observations was not even: relatively few counts had been made north of 10°30'S, or south of 15°00'S (Table 6.22).

Details of the number of bird counts per species per latitudinal half minute that have been incorporated into the overall data set are shown in Appendix Table 6.A.2, together with their time span. If information was available, counts were divided into breeding or non-breeding populations, but when there were no specific data, counts were classed as non-breeding.

6.4.2 Results

From the available data (1977 to present) we plotted the overall non-breeding and breeding distributions of each of 12 species of seabirds in the study area (Figures 6.13 to 6.24) in both wet (November–April) and dry (May–October) seasons. Overall monthly breeding records are summarised in Figures 6.25 to 6.27. In addition, the numbers of each species recorded since 1977 are shown separately for the Green Zone (closed to trawling since 1983) and the Lizard Island area (open to trawling) in Figures 6.28 to 6.39. The counting and reporting of birds in these two areas were more consistent than from other parts of the region due to research activities at both Raine Island and Lizard Island. Summaries of the main findings for each species are given below.

***Sterna bergii* (Crested Tern)**

This species is abundant throughout the northern Great Barrier Reef for the whole year (Figure 6.13). Crested Terns in the study area follow trawlers and feed extensively on trawl discards (Blaber et al. 1995). Nesting colonies have been recorded on more than 20 islands in the study area (Figure 6.13). Breeding takes place mainly during the wet season but significant numbers of birds also nest in the dry season (Figure 6.25a), although at fewer sites (Figure 6.13).

The numbers of Crested Terns in both the Green Zone and Lizard Island region have increased markedly since the 1970s, when counts were under 100, to the 1990's, with counts averaging about 1000 (Figure 6.28).

Sterna bengalensis (Lesser Crested Tern)

This species is widely distributed throughout the area in both wet and dry seasons but is much less common than *S. bergii* (Figure 6.14). Nesting was recorded on at least 15 islands in the study area. The birds breed almost exclusively in the wet season, with a peak in November–December (Figure 6.25b). No definite trend in the numbers of birds in the Lizard Island area was discernible, but in the Green Zone they have apparently declined since 1985 (Figure 6.29).

Sterna anaethetus (Bridled Tern)

Bridled terns are most abundant in the wet season but they have been recorded throughout the area in the dry season (Figure 6.15). Nesting, which was recorded on at least 25 islands (Figure 6.13), takes place almost exclusively in the wet season, with a peak in December (Figure 6.25c). Counts show considerable fluctuations with apparently little change in the Green Zone, but some evidence of an increase in the Lizard Island area (Figure 6.30).

Sterna fuscata (Sooty Tern)

This species is widely distributed in both wet and dry seasons, but is less common in the study area than *Sterna anaethetus* (Figure 6.16). Nesting has been recorded on about 12 islands, but with no clear seasonal pattern apparent. Breeding records cover 10 months of the year, with peaks in March, July and November (Figure 6.25d). Counts in the Green Zone show a marked decline in numbers between 1988 and 1995, while counts from the Lizard Island area fluctuate widely (Figure 6.31).

Sterna sumatrana (Black-naped Tern)

Black-naped Terns are very common. They have been recorded throughout the study area in both seasons (Figure 6.17). Most breeding records are from the wet season (Figure 6.17) with a peak in November, but they also nest in June–July (Figure 6.26a), especially in the northern part of the study area. No trends are evident in the count data (Figure 6.32).

Sterna dougallii (Roseate Tern)

This species has been recorded mainly in the inshore parts of the Green Zone and adjacent areas to the north and south. It is uncommon in the southern part of the study area (Figure 6.18). Nesting has been recorded on only five islands (Figure 6.18) and breeding takes place from March to May (late wet–early dry season) with a peak of activity in March (Figure 6.26b). The populations appear to fluctuate widely in numbers (Figure 6.33).

Sterna caspia (Caspian Tern)

This species is sparsely though widely distributed in the study area (Figure 6.19). The records on land in Figure 6.19 are from the centre of degree grids from the RAOU database — the actual observations may come from the coastal parts of these degree grids. Nesting, which has been recorded from about 14 places (Figure 6.19), takes place mainly in the dry season (Figure

6.26c). Numbers of birds in the Green Zone are low and relatively stable, but in the Lizard Island area numbers appear to have declined by almost an order of magnitude since 1977 (Figure 6.34).

Anous stolidus (Common Noddy)

This very common species is widely distributed in the Far Northern Great Barrier Reef in both wet and dry seasons (Figure 6.20). Nesting has been recorded in nine months of the year at more than a dozen localities, with most breeding taking place from March to July (Figure 6.26d). Population counts show much fluctuation and no trends are apparent (Figure 6.35).

Anous minutus (Black Noddy)

The Black Noddy is abundant throughout the area in both wet and dry seasons (Figure 6.21). Nesting has been recorded in 10 months of the year, with peaks in April, July and November (Figure 6.27a). Breeding has been recorded on at least 20 islands (Figure 6.21). As for Common Noddy, population counts fluctuate greatly and no trends are apparent (Figure 6.36).

Sula leucogaster (Brown Booby)

This is the most abundant and widespread sulid in the Far Northern Great Barrier Reef. It is common throughout the region in both wet and dry seasons (Figure 6.22). Nesting has been recorded from October to December and from March to July, with a pronounced peak in November (Figure 6.27b). No population trends are discernible from the count data (Figure 6.33).

Fregata minor (Greater Frigatebird)

This species has been recorded in only small numbers, mainly in the northern part of the study area (Figure 6.23), and no population trends are shown by the count data (Figure 6.38). The only recorded breeding sites are Raine Island in the Green Zone and Stapleton Island at 14°29'S. Nesting was recorded at Raine Island in July 1988, October 1994 and November 1994 (one pair each time) and literature records also list breeding from April to August (Taplin & Blaber 1993). Nesting at Stapleton Island was noted in April 1991 (five pairs) (Figure 6.38).

Fregata ariel (Lesser Frigatebird)

The Lesser Frigatebird is much commoner than the previous species. It has been recorded in large numbers in and next to the Green Zone and in the southern part of the study area in wet and dry seasons (Figure 6.24). There are very few records from the central area in and around Princess Charlotte Bay. Breeding appears to be concentrated mainly in the dry season, although considerable activity is also recorded for March and November (Figure 6.27d). No population trends are apparent from the count data (Figure 6.39).

Table 6.22 Total number of seabird counts per month and total number of sample days per 30° latitudinal stratum in the consolidated database.

Month	Counts (*n*)	Latitudinal range	Samples (*n*)
January	111	09°00–09°30	4
February	138	09°30–10°00	2°
March	216	10°00–10°30	5
April	172	10°30–11°00	20
May	225	11°00–11°30	78
June	234	11°30–12°00	99
July	224	12°00–12°30	37
August	157	12°30–13°00	33
September	7	13°00–13°30	40
October	188	13°30–14°00	41
November	340	14°00–14°30	64
December	378	14°30–15°00	129
December	0	15°00–15°30	8
December	0	15°30–16°00	5
Total	**2390**		**565 days**

6.5 Discussion

Quantity and composition of discards

In many prawn trawl fisheries, the quantity discarded is expressed as a ratio of the weight of discards to the weight of prawns. The ratio in our research trawls in the study area (Green Zone + adjacent areas to the north and south) averaged 6:1 in the inshore region and 10:1 offshore. High ratios of bycatch to prawns are found in all tropical commercial prawn fisheries in northern Australia (Table 6.23). These ratios are similar to those found in trawl fisheries for animals other than prawns elsewhere. In the North Sea, for example, beam trawlers fishing for ground fish discard at a ratio of 6:1 to 10:1, while in the North Sea trawl fishery for Nephrops, the ratio is around 8:1 (Garthe et al. 1996). The results of our commercial duration trawls indicated that inshore, a single prawn trawl could catch non-commercial invertebrates at around 21 kg hr-1 and fish at a rate of around 17 kg hr –1 while offshore the rates were 42 kg hr –1 for invertebrates and 13 kg hr –1 for fish. If we assume that trawlers fish for 10 hours each night towing two nets, then they would catch around 750 kg of potential discards in inshore trawling and around 1100 kg offshore in a nights fishing. If these data are combined with information on the number of days of trawling in the Far Northern Section (Table 2.05 in Chapter 2) we can obtain approximate upper and lower bounds for the amount of bycatch taken. According to Table 2.05, there is an average of around 16500 boat days in the Far Northern Section each year. If each boat day resulted in 750 kg of bycatch, the total would be 12 000 t. If each boat day resulted in 1100 kg of bycatch the total would be 18 000 t. We have to be cautious about this extrapolation because it is likely that the rates vary regionally and seasonally and we do not have sufficient resolution in the commercial fishing data to establish how much trawling takes place in each area. It is also not clear where a boundary should be drawn between inshore and offshore in some areas, for example between Princess Charlotte Bay and the southern boundary of the Far Northern Section. It is also possible that repeated trawling in the same area may result in some depletion of bycatch with a consequent reduction in the amount of discards. Finally, the catch rates are based on research trawl shots taken over the entire study area, data based solely on commercially fished grounds may yield different values.

The total amounts of discards from northern Australian prawn fisheries are small relative to the North Sea, where annual discards of unwanted catch and offal amount to 789 000 t from the fin-fish fishery and a further 156 000 t from the shrimp (Crangon crangon) beam trawl fishery. High ratios of discards are seen worldwide to be a serious environmental effect of trawl fisheries. In North American and Australian prawn (shrimp) fisheries, research has focused on ways of reducing the bycatch and, to a lesser extent, on finding uses for bycatch. Recently developed Bycatch Reduction Devices (BRDs) can largely eliminate large animals and reduce bycatch by from 20 to 30%, but, for the foreseeable future, there seems little likelihood that waste will be eliminated (Eayrs et al. 1997). Even if prawn fisheries can reduce the ratio of prawns to bycatch to 1:1, many thousands of tonnes of animals will continue to be discarded from prawn fisheries.

Table 6.23 Discards from prawn fisheries in northern Australia. Data for NPF from Pender et al. (1992); Torres Strait from Harris and Poiner (1990); Queensland east coast from Saila (1983); Moreton Bay from Wassenberg and Hill (1990); and Far Northern Section extrapolated from data collected in the Green Zone and known fishing days in the area. The estimated discard catch per night is for a single trawler.

	NPF	Torres Strait	Qld east coast	Moreton Bay	Far Northern Section
Quantity of discards per annum	30 000 t	4 630 to 6 930	18 000 t		12 000 – 18 000 t
Ratio of discards to prawns	8 – 21:1	4.4–9.3:1		About 6:1	6 – 10:1
Estimated discard quantity per trawler per night	1736 kg	1284 kg		288-360 kg	600-750 kg

The composition of discards from prawn trawlers has been analysed quantitatively in four areas in tropical and subtropical Australia: in the western section of the Northern Prawn Fishery (NPF) by Pender et al. (1992); in Torres Strait by Harris and Poiner (1990); in the offshore part of the Green Zone in the present study; and in Moreton Bay by Wassenberg and Hill (1990). Watson et al. (1990) reported results of a trawler-catch study off central Queensland, but their data was given as numbers rather than as weights and does not separate commercial crustaceans from discards. Nevertheless, their results are given as a general indication of bycatch composition in this region (Table 6.24). As can be seen, fish are the dominant discards in the NPF and Torres Straits but on the Queensland East coast, crustaceans also form a major part or even dominate the bycatch.

Table 6.24 Composition of discards expressed as a percentage by weight of the total for three taxonomic groups from five separate studies of discards. Northern Prawn Fishery (NPF) data is for the western Gulf of Carpentaria, Pender et al. (1992); Torres Strait, Harris and Poiner (1990); Green Zone offshore data, this study; and Moreton Bay, Wassenberg and Hill (1990). Data for central Queensland from Watson et al. (1990) is based on numbers, not weights, and includes commercial crustaceans.

	NPF	Torres Strait	Green Zone inshore	Green Zone offshore	Central Qld	Moreton Bay
Teleosts	85	52-68	72	60	34–41	8
Crustaceans	4	11	7	13	39–54	52
Cephalopods	2	<1	1	1	1	3

Attempts to use bycatch have had little success in tropical industrial prawn fisheries. As we have shown in this study, the bycatch contains many species and most of the animals are small. In addition, in northern Australia the catch is taken from warm water (commonly above 25°C) and trawlers operate far from the nearest port. In turn the ports are far from potential markets. Consequently, there is no economic incentive to keep bycatch other than components with a high value. Given these constraints, discarding the bycatch probably will continue in the tropical prawn fishery, at least in Australia.

Discard availability to seabirds

Although discards were available to scavengers in the study areas, their impact on the diets and feeding ecology of the various seabirds was not uniform. Some species—notably *S. bergii*—fed predominantly on discards in the trawling season, but others—such as *A. stolidus* and *H. caspia*—changed their diets little. Floating discards may be available for up to six hours after being discarded (Harris and Poiner 1990). Species such as *S. bergii*, *S. leucogaster* and *F. ariel* are actively opportunistic, feeding around trawlers during discarding, but *S. anaetheta* and *S. dougallii* may be passive discard feeders, taking floating discards some distance away from the site of dumping.

There is no evidence that the availability of discards has resulted in the birds taking larger specimens of their normal prey (Diamond 1978; Hulsman 1988; Blaber and Wassenberg 1989; Smith 1993). However, it may have affected feeding strategies. The greater availability of discards of similar taxa may have led to greater overlap in the diets of the seabird species. For example, the diets of *S. bergii*, *S. anaetheta*, *S. leucogaster* and *F. ariel* overlap, whereas previously this might have been minimised by behavioural or morphological characteristics. Ashmole and Ashmole (1967) stated that "competition is reduced mainly by differences in feeding methods"; this important paradigm may be less significant where a superabundance of food of a limited range of taxa is provided artificially, as with trawl discarding. Also, although discarding may not have greatly affected the sizes of prey taken (for there are still weight and size limitations, as well as differences in bill morphology [Hulsman 1988]), it may have changed the mix of prey species and could have affected feeding behaviour. For example, *S. bergii* now feed behind trawlers at night (Blaber and Wassenberg 1989) and *F. ariel*, instead of pirating from other species, pick up prey directly from the surface. Hence, as in the northern hemisphere (Furness et al. 1988), the availability and quantity of discards in tropical waters may cause major changes in the feeding ecology of some seabird species, changes that may be facilitated by the essential "dynamism of their niches" (Hulsman 1987).

Effects of prawn trawling on seabird reproduction

Fluctuations in the availability of prey are thought to have a marked impact on the timing of breeding in tropical seabirds (e.g. Seki and Harrison 1989; Morris and Chardine 1992; Smith 1993). As the quantities of bycatch on the northern Great Barrier Reef are large, it is important to find out whether the seabirds on the reef are affected.

In the Lizard Island area, the terns (except for *H. caspia*) breed in the summer when there is little or no trawling activity (Figure 6.11 and 6.12, Smith 1993). The young are usually fully fledged before the trawling season opens (Smith 1993; CSIRO unpublished data). However, *S. bergii*, the species that takes most discards, breeds later than the other species, and it may be significant that the largest bycatch is in March, when the juveniles are learning to forage. This could have two important consequences: firstly, the juvenile birds become conditioned to feeding on discards, and, secondly, all the "extra" food may reduce juvenile mortality rates. The huge increases in populations of *S. bergii* in the south-east Gulf of Carpentaria are thought to have been due to the development of the large prawn trawl fishery, which discards large quantities of bycatch (Walker 1992; Blaber and Milton 1994).

S. anaetheta and *S. sumatrana* breed earlier and eat fewer bycatch species; hence discards have probably had little impact on their breeding. Likewise, *H. caspia*'s breeding pattern is probably not affected by discards (Figure 6.11 and 6.12); it is a winter breeder in the Lizard area and Far Northern Section, as it is elsewhere in the world (Whitfield and Blaber 1978; Harrison 1983).

As Smith (1993) stated, the breeding of *S. bergii* in the Lizard Island area is considerably more synchronous than at other sites on the Great Barrier Reef. This is thought to be due to the brevity of natural food pulses sufficient to permit breeding. During the study period *S. bergii* in the Far Northern Section also bred in summer (when there were few discards), and at mid-year (Figure 6.11 and 6.12) (when there were many). More than half the food at this time consisted of trawl taxa, even within the closed zone (Figure 6.09). These data suggest that food supply may not influence breeding times.

The other tern species in the Far Northern Section that bred in winter as well as summer were *A. stolidus*, *S. anaetheta*, *S. sumatrana* and *S. dougallii*. The first three of these took few or no discards, but—although our sample sizes were relatively small—about half *S. dougallii*'s diet consisted of benthic gobies. However, *S. dougallii*, which bred during the fishing season, is an unpredictable species throughout the world, particularly on the Great Barrier Reef (Smith 1991). In the northern hemisphere its breeding may be controlled by prey availability (Safina et al. 1988). There was high mortality of juvenile *S. dougallii* at breeding colonies in the Far Northern Section during the study period (Milton et al. in press). This may have been caused by fluctuations in food supply, possibly influenced by changing availability of discards, but other factors such as weather conditions, particularly wind-speed and sea-surface conditions, can affect the fishing ability of terns (Dunn 1973).

Breeding records (1979–87) for the three *Sula* species and *F. ariel* show that they breed for most months of the year in the closed zone of the Far Northern Section (Taplin and Blaber 1993). During our study they nested during times of declining as well as increasing abundance of bycatch. Although *S. leucogaster* and *F. ariel* from colonies in the closed zone forage for discards from the trawling grounds, the quantities are small and there seems little evidence that discarding influences their times of breeding.

While it is apparent that discards have changed the diets of some seabird species in the northern Great Barrier Reef, there is little evidence that they have directly affected the timing of breeding, despite the seasonal nature of bycatch availability. Breeding cycles are probably still determined mainly by the sharp peaks in abundance of pelagic prey (Smith 1993). Nevertheless, the provision of discards may have increased the overlap in the diets of most species and influenced the feeding strategies of at least *S. bergii, S. leucogaster* and *F. ariel*. Any effects on population sizes, such as have been reported in the south-east Gulf of Carpentaria (Walker 1992), are harder to define (Ryan and Molony 1988) and are reported on in the next section.

The large historical data set used for this report has obvious limitations in terms of the variability in the number of sampling days, as well as unknown levels of accuracy in reporting.

Despite these shortcomings, however, the overall coverage of the area, both geographically and in time, is quite comprehensive, particularly for the counts for the two areas shown in Figure 6.13–6.24. Several conspicuous features emerge from the data.

Firstly, the seabirds can be divided broadly into those that are common and widely distributed in the area (*Sterna bergii*, *S. bengalensis*, *S. anaethetus*, *S. sumatrana*, *Anous stolidus*, *A. minutus* and *Sula leucogaster*) and those that are less common or are more locally distributed (*Sterna fuscata*, *S. dougallii*, *H. caspia*, *Fregata ariel* and *F. minor*; Figure 6.13–6.24).

Secondly, large annual fluctuations in numbers are a feature of both groups. However, Crested Tern (*Sterna bergii*) is the only species that has clearly increased in numbers; two others—Bridled Tern (*S. anaethetus*) and Black Noddy (*Anous minutus*)—might have increased, but the data are equivocal. Large increases in the numbers of Crested Terns in the south-east Gulf of Carpentaria since the 1970s have been attributed to a greatly increased availability of food provided in the bycatch of prawn trawlers (Walker and Warnett 1992; Blaber and Milton 1994). In far northern Great Barrier Reef waters, the size of the increase in this species's numbers may similarly result from discards. Prawn trawling in this region began in the late 1970s (Matilda and Hill 1981; Williams 1980) at the time the Crested Tern numbers started to increase. During the early 1980s trawl effort increased by between 30 and 70%, particularly in the Princess Charlotte Bay area just north of Lizard Island (Beurteaux and Coles 1988). The trawl season, and hence discarding, begins in February when Crested Tern chicks are fledging; it was previously postulated (Blaber et al. 1995) that this timing may substantially affect the breeding success and increase the survival rate of young birds.

The count data for other species that scavenge discards, such as the Common Noddy, Brown Booby and Lesser Frigate Bird, show no definite trends—either populations of these species are not responding to increased availability of food, or perhaps the count data are not sensitive enough to reveal any changes in numbers.

Attributing changes in population size to fishing activity in the Great Barrier Reef must be viewed critically because patterns of abundance of tropical seabirds are affected by a wide variety of non-anthropogenic factors, including nutrient enrichment and productivity (Dunlop et al. 1988; Ricklefs 1990), cyclones (King et al. 1992) and the ENSO phenomenon (Valle et al. 1987).

No information is available on any changes of the first kind, but cyclones are well-monitored and relatively few occurred in the study area between 1975 and 1995. Although cyclones can have a devastating local effect on breeding colonies that are directly in their path (King et al. 1992), there is no evidence that cyclones in the study area affected seabird populations. For example, any breeding after April and before December is outside the cyclone season. The ENSO cycle, which is much shorter than the study period, also appears to have had little influence.

Thirdly, numbers of Lesser Crested Tern and Sooty Tern in the Green Zone have declined since the mid-1980s, while Caspian Tern numbers in the Lizard Island area have declined since 1977 (Figures. 6.29 and 6.31). The reasons for this are not known but might relate to changes in the bird's distribution and movements. For example, large fluctuations in the numbers of Lesser Crested Tern and Sooty Tern in the Lizard Island area are indicated (Figures 6.29 and 6.31). It is also possible that the large increases in Crested Tern numbers could affect other species by increasing competition for food and, perhaps more importantly, for nesting sites (although in the case of the Caspian Tern, the main breeding seasons do not overlap). Food availability has generally been believed to be more important than nest-site competition in determining population sizes and breeding seasons in tropical seabirds (e.g. Buckley and Buckley 1980; Diamond and Prys-Jones 1986) because tropical waters are usually less rich in food than those of higher latitudes. The provision of large quantities of additional food in the form of trawl discards could, theoretically, change this situation, but it may have allowed the populations of Crested Terns to increase sufficiently to put pressure on available nest-sites, competing with those species that take few or no discards. Competition may not be restricted only to nest sites; interference competition has been reported among foraging Roseate Terns and Common Noddies in Puerto Rico, with the large numbers of Common Noddies adversely affecting the foraging success of Roseate Terns (Shealer and Burger 1993).

An important feature evident from the data relates to breeding seasons. The seabirds appear to fall broadly into three groups: mainly wet season (summer) nesters (Crested Tern, Lesser Crested Tern, Bridled Tern, Black-Naped Tern and Brown Booby); dry season (winter) nesters (Caspian Tern, Greater Frigate Bird, Lesser Frigate Bird), and species that may nest in almost any month of the year (Sooty Tern, Common Noddy, Black Noddy). These data do not differ greatly from those reported for other regions of the Great Barrier Reef (King et al. 1992; Smith 1990 1993) and for other parts of the tropics. For example, the Common Noddy, which breeds in most months of the year in the northern Great Barrier Reef, is also recorded nesting in most months in Hawaii (Megyesi and Griffin 1996).

Some breeding of Sooty Terns is in progress in almost every month of the year in the far northern Great Barrier Reef, as it is further south at Michaelmas Cay (King et al. 1992). Crested Terns have a pronounced wet season breeding peak in the Great Barrier Reef (this study; Smith 1993; Taplin and Blaber 1993; King et al. 1992), in the south-east Gulf of Carpentaria (Walker and Warnett 1992) and as far away as Mozambique and South Africa (Urban et al. 1986).

The breeding success and mass mortalities of Roseate Terns in the study area have already been documented (Milton et al. 1996). Most breeding records are from the late-wet and early-dry season, but success is highly variable. The authors concluded that conditions in northern Australia are rarely favourable for the rapid growth and breeding success of Roseate Terns. Pelagic fish populations around inshore islands in tropical Australia may be able to support only limited numbers of Roseate Terns during the breeding season, which would make the north-eastern Australian populations of this globally threatened species extremely vulnerable to changes in the availability of their prey during that season. In the Azores, Roseate Terns have relatively specialised nest-site requirements, and competition may reduce the number of suitable sites in mixed-species colonies (Ramos and Delnevo 1995). Furthermore, this species may rely on predatory fish or other birds to increase prey availability during the breeding season (Shealer 1996). Whether Roseate Terns are affected by discards from trawls is unknown, but in the study area it does eat discards (Blaber et al. 1995). It is, therefore, possible that rapid increases and decreases in prey availability caused by trawling and increased competition from other species may add to the natural factors influencing the breeding and population size of Roseate Terns.

Despite pronounced seasonal peaks in the breeding activity of the species included in this study, most also show some nesting activity at other times of year. This suggests that they may be able to breed at any time and are sufficiently flexible to take advantage of the onset of conditions suitable for breeding. The relationship between such flexibility and the possible influence of the provision of extra food resources from discarding may be a key, together with whether a species takes discards or not, to understanding the variable effects of trawling on the populations of different species. There are at present, however, no definite indications that trawl discarding directly influences breeding seasonality, much of which may be locked into endogenous rhythms. There is evidence (see also Blaber et al. 1995) that extra food in the form of trawl discards may influence breeding success and hence population sizes of some species.

Animals that float are vulnerable to being eaten by surface scavengers, regardless of whether or not they are alive. Trawling, and hence discarding, takes place at night in the northern Great Barrier Reef region because the main target species of prawns are caught at night. We saw little of surface scavengers at night in the Green Zone. This is unlike in the Moreton Bay fishery where birds and dolphins commonly feed on discards at night (Wassenberg and Hill 1990) or the Gulf of Carpentaria where shoals of small (about 1 m total length) sharks swarm around the stern of trawlers at night (CSIRO unpublished observations). Thus at present we do not know the extent to which floating discards are taken at night. Those that are not scavenged would still be floating at dawn—previous studies have shown that floating discards stay up for a long time (Hill and Wassenberg 1992). In addition, the final trawl of the night is hauled around dawn and its floating discards would be on the surface in daylight. Because of the long duration of commercial trawls, there are usually only around 4 trawls each night. Thus at least 25% of the discard is dumped in daylight. During daylight hours we saw seabirds, dolphins and sharks scavenging discards on the surface.

One of the findings of the present study, has been the apparent link between populations of Crested Terns and prawn trawling (Blaber et al. 1995). During the trawling season over 40% of the diet of Crested Terns, around 15% of the diet of Lesser Frigatebirds and 4% of the diet of Brown Boobies consisted of species that probably came from trawler discards.

The main discards fed on by seabirds are the fish; these make up 74% of inshore discards and 48% offshore. However, not all fish float. Our experiments showed that 43% of inshore discard fish and 22% of offshore discard fish floated. Thus only 32% of inshore discards (43% of 74%) and 11% of offshore discards (22% of 48%) are floating fish. The seabirds do take some of the discards that would potentially float as shown by the presence of discard prawns in their diets. These could only be taken if the birds are foraging very close to the boat and would only apply to daytime trawling discards. It appears therefore that the overwhelming proportion of discards taken by birds would be floating individuals.

We know from previous work that seabirds are selective in the size of prey taken. For example, Blaber and Wassenberg (1989) found that Crested Terns preferred prey with a mean length of 83 mm (SD 21). Wassenberg and Hill (1990) offered scavenging Silver Gulls a range of sizes of whiting and found that the proportion taken fell from 100% of fish smaller than 180 mm to 0% of fish larger than 220 mm. Even relatively large birds such as the two species of Frigatebirds collect prey mainly in the weight range from 6 to 102 g (Diamond, 1990). Selectivity will reduce the amount of discards that are available to seabirds if some of the discards are larger than the preferred size.

In order to estimate the effect of size selectivity on the proportion of floating discards that are liable to be taken by seabirds, we analysed the length composition of fish in the diets of the three species of seabirds known to scavenge trawler discards in the northern Great Barrier Reef region—Crested Terns, Brown Boobies and Lesser Frigatebirds. These data were collected as part of this study of seabird diets. We used data only from regurgitated pellets or regurgitated prey collected during the trawling season. The results are given in Figure 6.40. The size frequency of floating discards as based on the buoyancy experiments on discards collected from 160/165 min duration trawls is given in Fig 6.41.

Figure 6.40 shows that Crested Terns in the northern GBR feed on fish that are mostly less than 12 cm in length. This size limit excludes approximately half of the floating discards. Brown Boobies feed on a wider size range of prey, but most of the fish in their diet are smaller than 10 cm (Figure 6.40). Although Lesser Frigatebirds do take fish larger than 10 cm (Figure 6.40), these accounted for only 27% of the diet by number. Blaber et al. (1995) found that 41.5% of the diet of Crested Terns could have come from trawler discards, for Lesser Frigatebirds the percentage was far lower—14.5%—while for Brown Boobies the percentage was minor—3.8%. Thus, in terms of the fate of discards, it appears that only around half of the discards fall within the size range for prey of the three main seabird scavengers in the northern GBR.

We can now estimate the proportion of discards that are available to seabirds by factoring in the proportion that are fish, the proportion of fish that float, and the proportion of fish that are in a suitable size range (Table 6.25).

Table 6.25 Calculation of percentages of discards available to seabirds. The 'net available' is the product of the fish as a percentage of total discards and of each of the following factors.

	Inshore	Offshore
Fish as % of total discards	72	60
% of fish that float	44	24
Approximate % right size	50	50
Net available to seabirds	16	7

Because it is unlikely that seabirds eat all of the prey that is potentially available, we conclude that seabirds are unlikely to be a major sink for trawler discards. Wassenberg and Hill (1990) estimated that, in Moreton Bay, seabirds took less than 10% of discards. In the North Sea, seabirds consume around 30% of discards by weight (ICES CM 1997/L:3, using data from Garthe et al. 1997; Camphuysen et al. 1995; and Walter and Becker in prep.). It is interesting to note, however, that, even though seabirds may take only a minor part of the discards, this quantity may be enough to affect the population size of at least one species—Crested Terns—in the northern GBR.

What happens to the large number of floating fish that are not theoretically available to seabirds? Some proportion is taken by the other surface scavengers that we observed—dolphins and sharks. However in some areas of Queensland there are persistent complaints about discard fish washing up on beaches. In these areas at least, the surface scavengers do not account for all floating discards.

In our tests of Green Zone discards, between 60 and 72% of fish and nearly all of the invertebrates sank. The fate of these sinking discards is determined largely by whether or not they can survive the process of being trawled and exposed to air on deck. On the basis of previous experimental studies, we have assumed that nearly all fish are dead when discarded (Hill and Wassenberg 1990). Invertebrates, especially crabs and bivalves, generally have good survival after being trawled and, because these two groups made up most of the invertebrate discards, we can assume that a large proportion of the invertebrate discards are alive when they reach the seabed.

Some discards—alive and dead—could be scavenged in midwater. We know little about midwater scavenging of discards in any prawn fishery. In the two areas—Torres Strait and Moreton Bay—where this has been investigated, the amount of midwater scavenging is low or negligible (Hill and Wassenberg 1990; Wassenberg and Hill 1990). The main midwater scavengers appear to be sharks. One of the factors in the low rate of midwater scavenging is the short time that discards spend in the water column because of their relatively high sinking speed (around 6 m min-1) and the shallowness of the water (mostly around 20 m). Thus most sinking discards probably reach the seabed.

Discards from prawn trawling are spread over large areas and the density on the bottom is quite low, around 9 kg per 100 m travelled by the trawler (chapter 6.2). Dead discards reaching the seabed are eaten by a range of benthic scavengers. Some of these are present in the immediate area, but, in cases where trawling continues in an area, other scavengers may be attracted to the disturbed area. For example, the hermit crab *Pagurus bernhardus* is found in higher densities in trawl tracks than in adjacent areas (Ramsay et al. 1996). In the Repeat-trawl experiment, we found that the numbers of two of the most common benthic scavengers—the fish *Pentapodus paradiseus* and *Nemipterus furcosus* increased with successive trawls suggesting they were moving into the area of trawl disturbance (See Chapter 5).

The numbers of both of these species initially did not show any trend, but they then increased over the course of the experiment, suggesting that the fish were attracted to the area of disturbance caused by the trawl. This attraction would not have been to discards in this case because the entire catch was retained at the end of each shot. The fish were presumably responding to the general disturbance, and possibly an increased availability of food from animals disturbed or injured by the net passing over the seabed and from small animals or fragments that had passed through the net. This suggests that the scavengers of discards are made up of animals that are attracted to the disturbance caused by the net as well as to the presence of discards.

Our underwater television observations showed three main groups of benthic scavengers offshore—teleost fish, sharks and crabs. This suite of benthic scavengers is similar to those identified in the nearby Torres Strait (Hill and Wassenberg 1990). Some of the most common species of fish caught in trawl nets were also the main scavengers of baits on the seabed in the Green Zone, e.g. Nemipterus furcosus, Pentapodus paradiseus and Lethrinus genivittatus. Other species commonly caught in the trawls, such as Paramonacanthus choirocephalus and species of Upeneus, were never seen to feed on the bait. In contrast, some species such as Lutjanus sebae and small sharks around 1 m in length were common as scavengers but rarely caught in prawn trawls. There is one group of benthic scavengers that we did not record but that may be important, especially in feeding on fragments and remains left by other scavengers. These are small crustaceans and especially isopods. The resolution of the underwater camera system we used was inadequate to identify isopod activity but Keable (1995) found intensive scavenging by cirolanid isopods of baits in traps set at a depth of 12 m on the bottom around Lizard Island. More than 2000 individuals were attracted to some baits and they were able to strip the flesh from a 38 g fish to bare bones within 2 h. Isopods may be major benthic scavengers of trawler discards in the tropics.

The fate of discards in the region of the Green Zone is generally similar to that in the nearby Torres Strait fishery, but very different from the more temperate southern Queensland Moreton Bay fishery. In all areas the key factor in deciding fate is the composition of discards. In areas where fish are a major component, then mortality is high. This is the case in the Green Zone and Torres Strait. In Moreton Bay by contrast, fish make up only a minor part of the catch which is dominated by crustaceans instead. In Moreton Bay survival of discards is quite high. Composition is also a key factor in deciding what proportion of the discards float since nearly all floating animals are fish. In all areas these are scavenged by the same suite of scavengers – seabirds, dolphins and sharks. In areas of intense trawling, some of these scavengers show distinct behavioural changes associated with the availability of discards as food. In the case of dolphins, they have learned to follow trawlers and, in Moreton Bay, to follow boats only after hauling of the net has commenced. In the case of seabirds the two changes to behaviour are to forage at night and, in the case of Frigatebirds, to collect discards themselves rather than relying on pirating from other birds. The level of trawling in the vicinity of the Green Zone is relatively low and we did not see evidence of night time scavenging by seabirds and only minimal scavenging at night by sharks and dolphins and even this did not seem to be directed at the trawler in the sense of the animals following the vessel because of the possibility of finding food. We did see Frigatebirds scavenging discards, but because they can forage over wide distances, this behaviour may have been learned in the nearby more intensively trawled grounds in Torres Strait or Princess Charlotte Bay. Consequently we cannot ascribe any change in behaviour of scavengers to the availability of discards from trawling in the vicinity of the Green Zone. The only impact that we could identify on scavenger populations was the increase in the population of Crested Terns. Although there is no direct evidence that the two are linked, the correspondence between the timing of the increase in population and the start of prawn trawling in the region, suggests that they may be.

Impacts of discarding

Pender and Willing (1989) estimated that, on average, each trawler in the Northern Prawn Fishery discards approximately 1.7 t of animals each night. In the Torres Strait—which is close to the Green Zone—the quantity is between 0.8 and 2.1 t each night (Harris and Poiner 1990). Thus, on prawn trawl grounds, large amounts of discards are available to scavengers. Food is frequently a limiting factor in animal populations and so it is not unreasonable to expect that, if food supplies are increased, populations of some of the beneficiaries may also increase.

The present study of the Green Zone has found increases in population size of at least one species of seabird—Crested Terns—and there are indications that feeding on discards may have contributed to this increase. It has been estimated that in the North Sea about 340 000 seabirds may be sustained by discards from offshore fisheries (Walter and Becker in prep.). However, as we have shown above, in the region of the Green Zone, seabirds potentially consume less than 20% of the discards.

Although the estimated tonnages of discards from tropical prawn fisheries in Australia is high—e.g. 30 000 t per annum in the Northern Prawn Fishery (Pender and Willing 1989)—the area occupied by these fisheries is very large. In the case of the Northern Prawn Fishery, trawling was recorded in 200 grid squares each of 6 × 6 n.mile (= 123.6 km2; AFMA logbook data). Thus the total area of the fishery is 24 720 km2. If we spread the 30 000 t of discards over this area it amounts to 1213 kg km¯2 which is equivalent to 1.2 g m¯2 over the six months' trawling season. A proportion (8 to 40% by weight) of discards float, and so the amount reaching the seabed is even less. The region around the Green Zone is not heavily trawled and so the density of discards is probably lower than in the Northern Prawn Fishery. Thus, although the tonnage is large, it is widely dispersed both in space and in time. The animals that are mostly likely to be able to benefit from such a widely dispersed food source are those that are able to locate discards over large areas. The seabirds are clearly in this category as they are capable of searching tens or hundreds of square kilometres a day. Dolphins and sharks can also locate discards through following or being attracted to trawlers, but their effective scavenging distance is probably only kilometres per day. In many parts of northern Australia, groups of small sharks and dolphins are a common sight around trawlers when they are discarding. Dolphins and sharks may adopt a strategy of remaining in areas where discarding takes place and then targeting trawlers. It is likely that sharks can detect and locate discards from at least several hundred metres down current, and so they can also target discards on the seabed. Small benthic fish and invertebrates, by contrast, are capable of more limited movements and so are less able to benefit from discards. However, as we have shown, even these species can move into areas of concentrated fishing. In concentrated fisheries—Moreton Bay, for example—in which trawling and discarding takes place in a relatively limited area, even scavengers that can range over only a relatively small distance can benefit from discards. Examples include the blue swimmer (Portunus pelagicus) in Moreton Bay (Wassenberg and Hill, 1987) and the hermit crab Pagurus bernhardus in the Irish Sea (Ramsay et al. 1996). The latter species moves into areas disturbed by trawls and feeds both on animals damaged by the trawls and on discards.

These differences in foraging distances can be used to separate scavengers of discards into three groups—seabirds in the first group, dolphins and sharks in the second, and small fish and invertebrates in the third (Table 6.26). This grouping assists in making general predictions about the likely indirect impacts of discarding. We could reasonably expect impacts on species in the first group even with only moderate levels of trawling because of their ability to find discards a long way from their nesting or roosting sites. The present study has identified a possible impact on populations of Crested Terns. The form of the impact is increased population size, presumably as a result of a greater availability of food. This could, of course, have negative impacts on other seabird species if it results in greater competition for nesting sites or for food at times when trawling and discarding are not occurring. Other negative impacts could result from increased exposure to parasites through feeding on benthic species that are not part of the normal diet (Groenewold et al. 1996).

Table 6.26 The three groups of scavengers of trawler discards and the possibility of their populations being affected by scavenging.

Scavenger group	Composition of group	Distance of daily scavenging activity	Impact on populations relative to trawling intensity
Group A	Seabird species that take discards	Tens of kilometres	Possible even in lightly fished areas because of ability to forage widely
Group B	Dolphins and sharks	Kilometres	Possible in areas of regular trawling because they can concentrate in these areas
Group C	Small fish and invertebrates on seabed	Tens of metres	Likely only in areas of regualr trawling

Because of the more restricted scavenging range of the second group we would expect impacts only in populations that forage in areas of high fishing intensity. If trawling effort is low or very dispersed, there may be no measurable impact. However, this group is capable of moving into areas where discards are available. In Torres Strait, for example, dolphins were commonly seen in an area open to trawling where they scavenged discards, but they were not seen in an adjacent area that is closed to trawling (Hill and Wassenberg 1990).

The third group—small benthic fish and invertebrates—range over restricted distances, but are often widely distributed. They are probably not affected by discards as their opportunity to feed on discards is limited by their restricted foraging range. Thus, although the group as a whole may consume a large proportion of discards, the supply to any individual is small and so there may be no discernible impact on the population. In areas of concentrated trawling, however, the amount of discards in a given area may be sufficient to increase significantly the amount of food available to individuals. In Moreton Bay, for example, the diet of blue swimmer crabs, Portunus pelagicus, changes from a "natural" one over weekends when trawling is not allowed, to one dominated by discards during the week when trawling is permitted (Wassenberg and Hill 1987). Ramsay et al. (1996) found that hermit crabs in areas disturbed by trawling had more food in their guts than did crabs in untrawled areas. We do not know if feeding of discards affects benthic scavenger populations. Experimental enhancement of food supply to three crab species on the Pacific coast of the USA resulted in an increase in the fecundity of the populations (Fusaro 1978; Wenner et al. 1987). It is not known whether this resulted in overall population growth. These data indicate that increased availability of food to benthic scavengers may have complex impacts on populations. It is reasonable to expect that high densities of discards in a small area could impact on populations of benthic scavengers even if the individuals have a restricted foraging range.

We conclude that, in the broader Great Barrier Reef region, feeding on trawler discards will have an impact on a few species of seabirds. It probably affects shark and dolphins in some areas. Impacts on small benthic fish and invertebrates are probably uncommon and restricted to areas of high trawling intensity. Thus the available information suggests that trawl discards are not a major environmental perturbation in the Far Northern Section of the Great Barrier Reef.

This should not be taken as providing support for continuation of present practices. Trawling is killing many thousands of tonnes of animals each year. In addition we do not know whether the discards include species that are particularly vulnerable to disturbance. Bycatch Reduction Devices (BRDs) currently available can reduce the bycatch by around 20% and it is likely that this figure will improve with new developments. Technological improvements in handling of the catch may also contribute to better survival. Industry and managers need to continue to encourage the development and introduction of more efficient BRDs with the eventual aim of reducing the amount of bycatch to negligible levels.

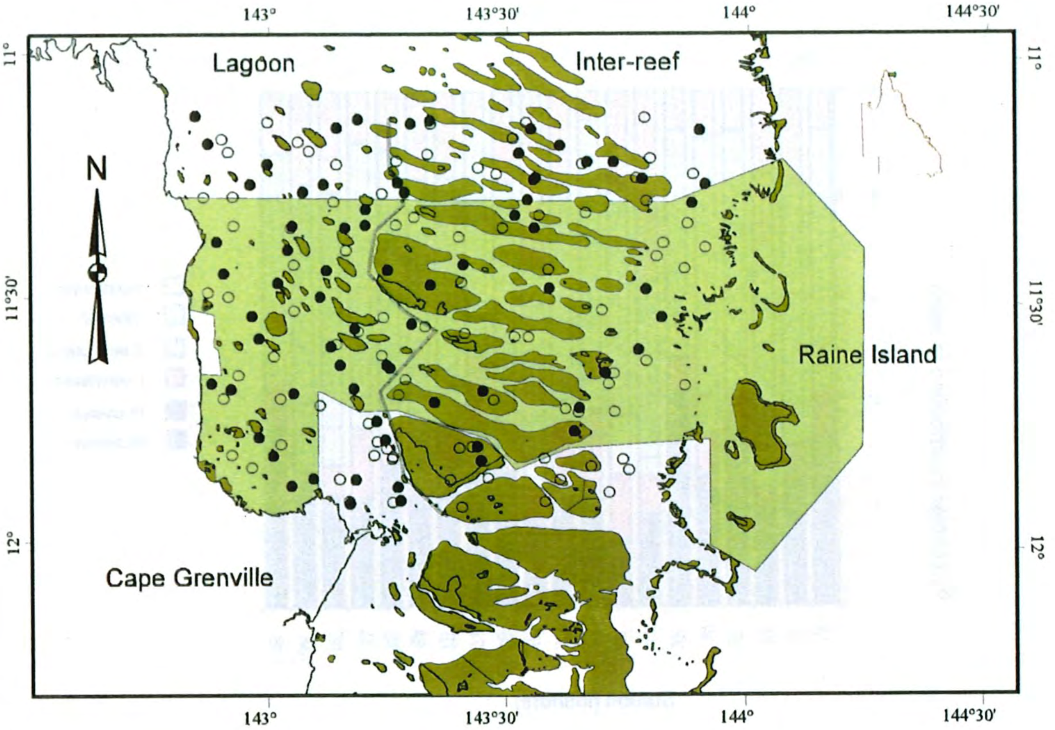


Figure 6.01 Sites from which bycatch samples were collected using 30 min duration trawls. There were 79 inshore and 43 offshore stations.

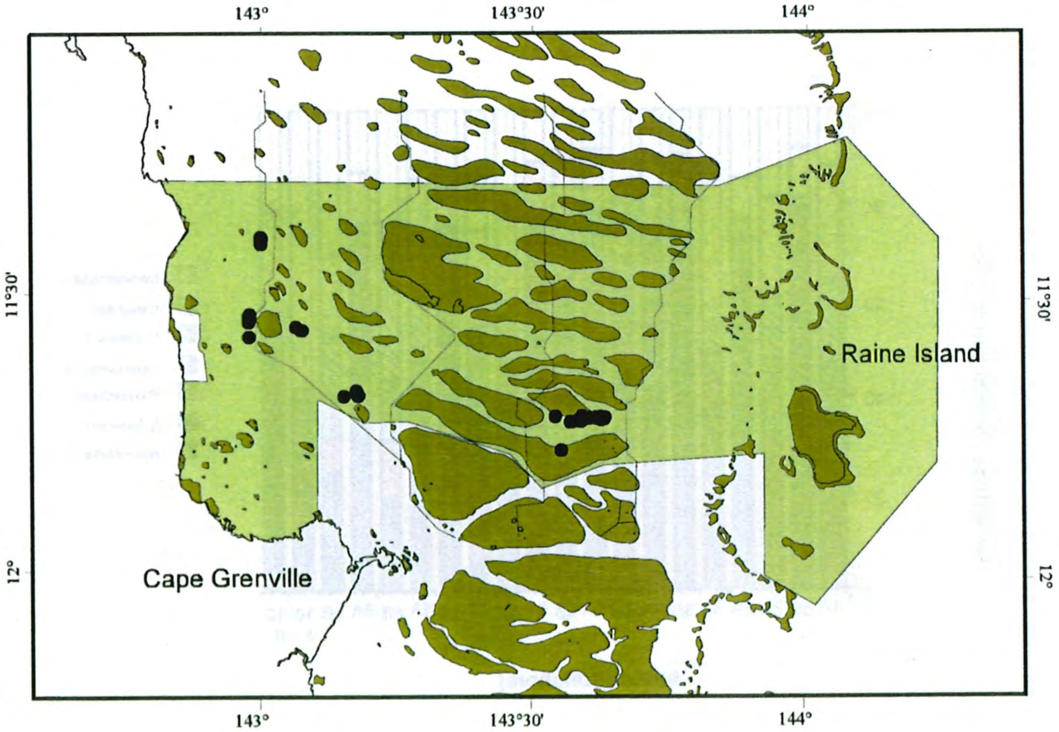


Figure 6.02 Sites from which paired short (30 min) and long (165 min) trawl samples were collected for determining whether trawl duration affected bycatch composition. There were 10 inshore and 10 offshore stations. Because of the scale of the maps, many of the dots showing position overlap.

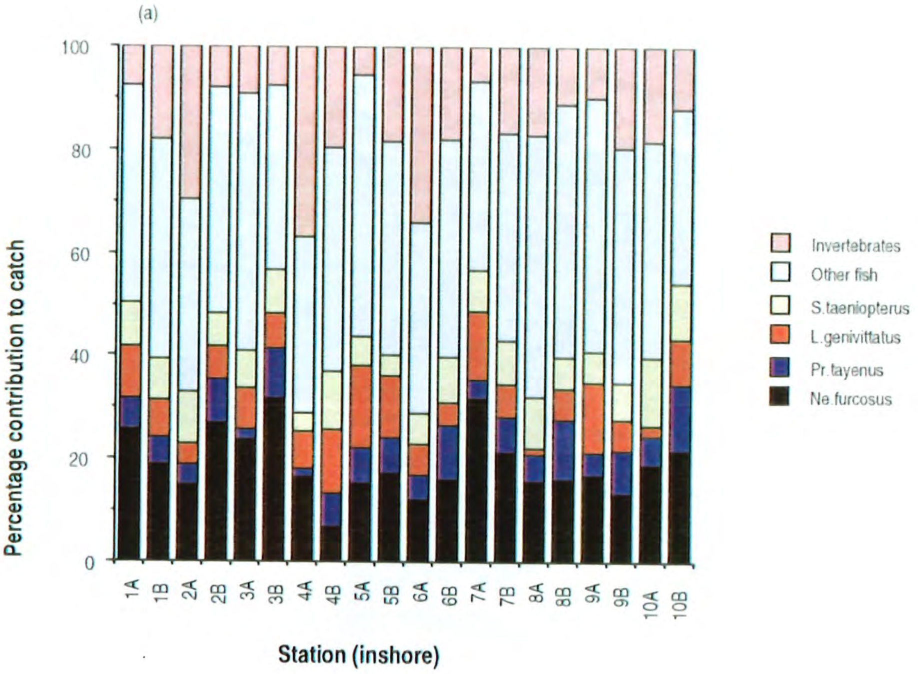


Figure 6.03 Composition of bycatch at 10 inshore stations. Paired tows were made at each station number. Samples labelled A were from 30 min duration trawls, samples labelled B were from 165 min trawls.

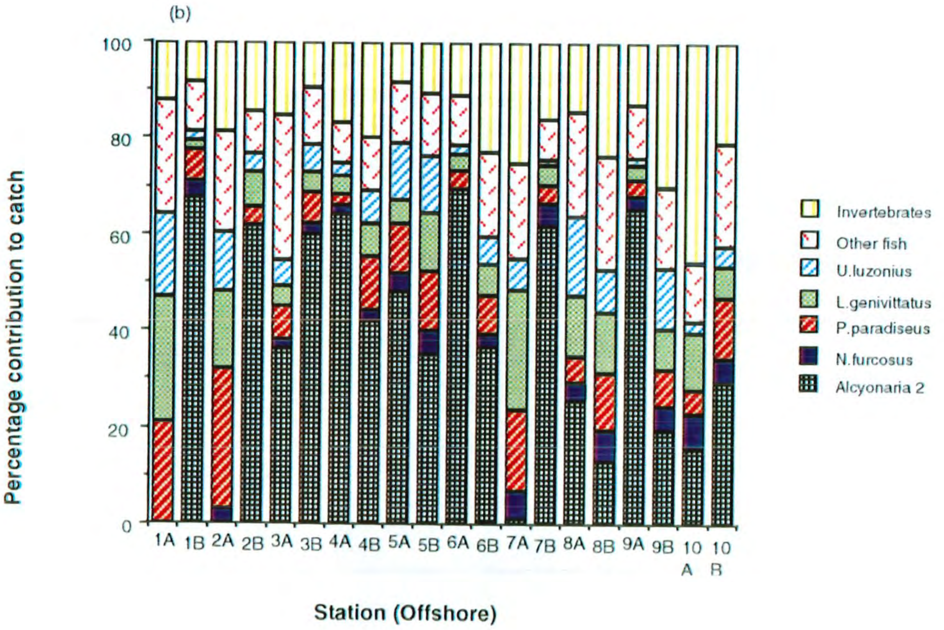


Figure 6.04 Composition of bycatch at 10 offshore stations. Paired tows were made at each station number. Samples labelled A were from 30 min duration trawls, samples labelled B were from 165 min trawls.

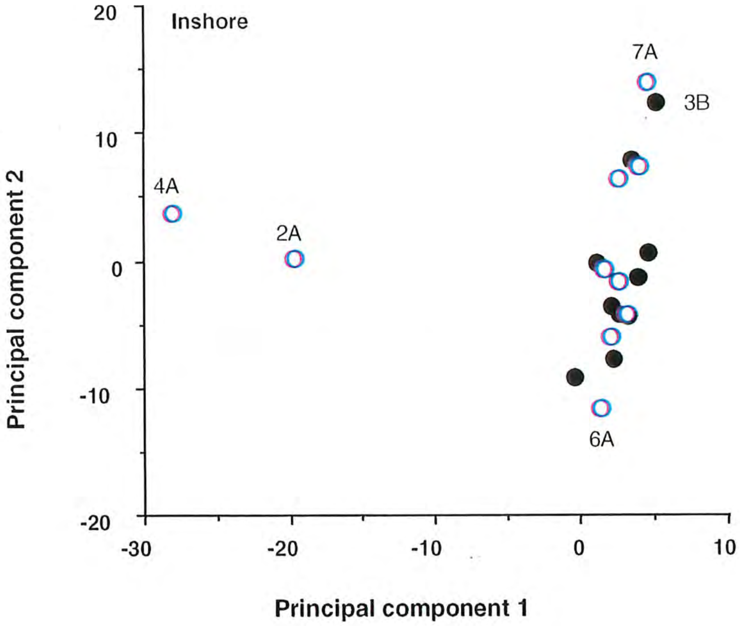


Figure 6.05 Principal component scores for bycatch collected from inshore trawl stations

Solid circles = long tows, open circles = short tows: Extreme stations have been labelled

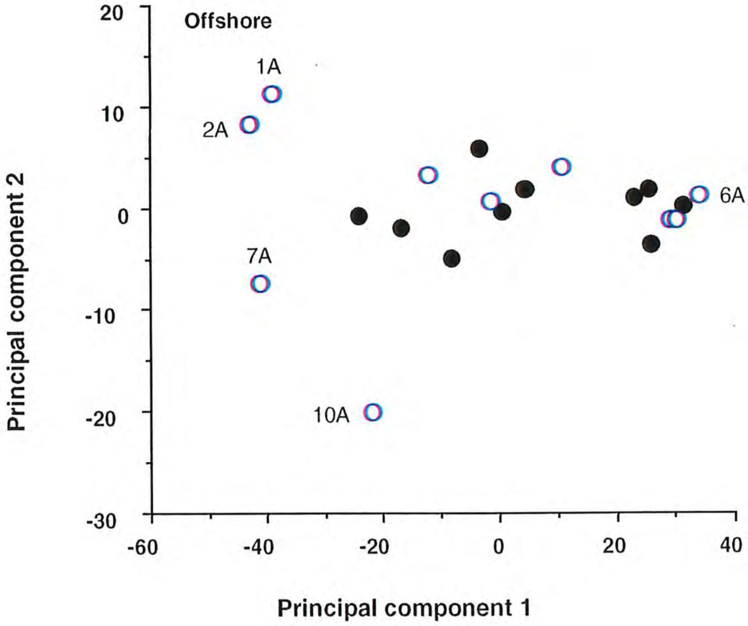


Figure 6.06 Principal component scores for bycatch collected from offshore stations.

Solid circles = long tows, open circles = short tows: Extreme stations have been labelled.

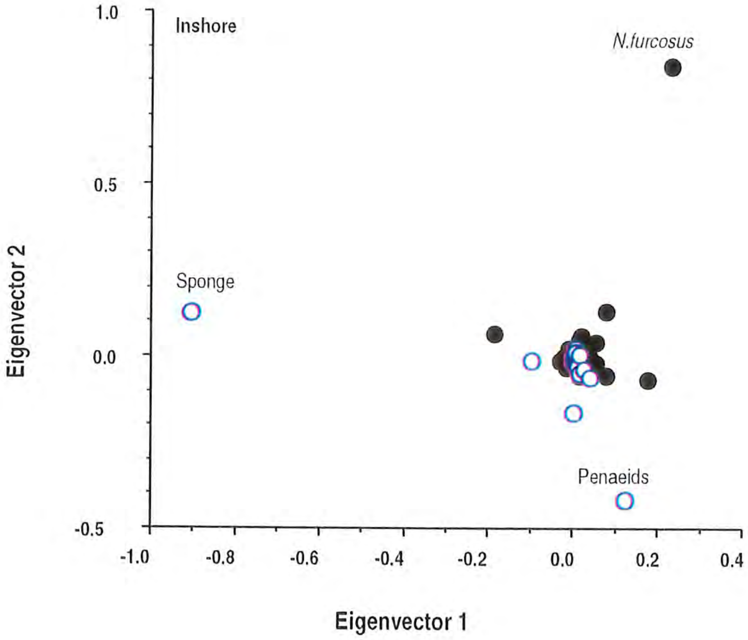


Figure 6.07 Species eigenvector coefficients for inshore stations.

Solid circles = long tows, open circles = short tows.
Groups with extreme values have been labelled.

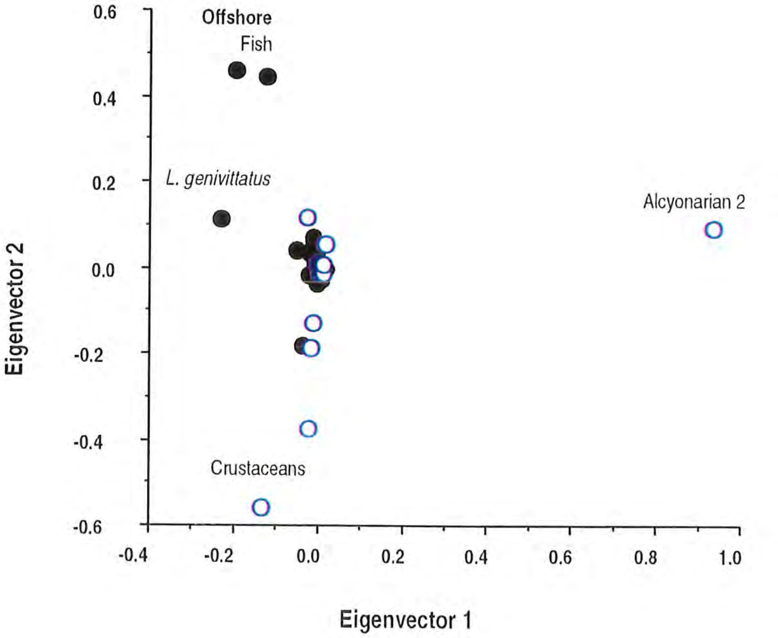


Figure 6.08 Species eigenvector coefficients for offshore stations.

Solid circles = long tows, open circles = short tows.
Species with extreme values have been labelled.

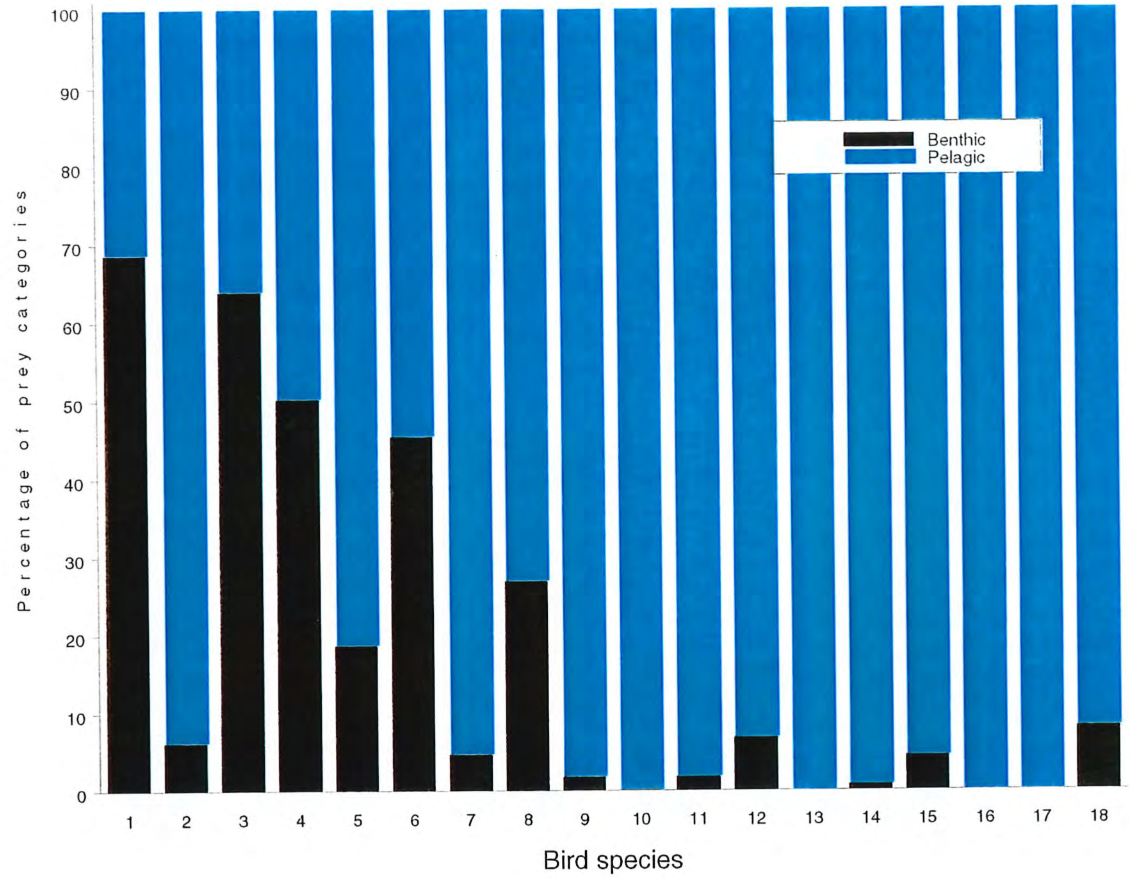


Figure 6.09 Proportions of pelagic and benthic prey for 18 seabird species in areas open and closed to trawling.

1 *S. bergi* at Lizard Is. In open trawl season; 2 *S. bergi* at Lizard Is. In closed season; 3 *S. bergi* in Far Northern Section trawl grounds; 4 *S. bergi* in Far Northern Section closed zone; 5 *S. Bengali*; 6 *S. Dougali;* 7 *Hydroprogne caspa*, 8 *S. Anaetheta*; 9 *S. sumatrana* at Lizard Is.; 10 *S. sumatrana* in Far Northern Section; 11 *A. stolidus* at Lizard Is. in closed season; 12 *A. stolidus* at Lizard Is. in trawl season; 13 *A. stolidus* in the Far Northern Section; 14 *S. leucogaster* in Far Northern Section trawl grounds; 15 *S. Leucogaster* in Far Northern Section closed zone; 16 & 17 *S. Sula* and *S. Dactylatra* in Far Northern Section closed zone; 18 *F. Ariel* Far Northern Section closed zone.

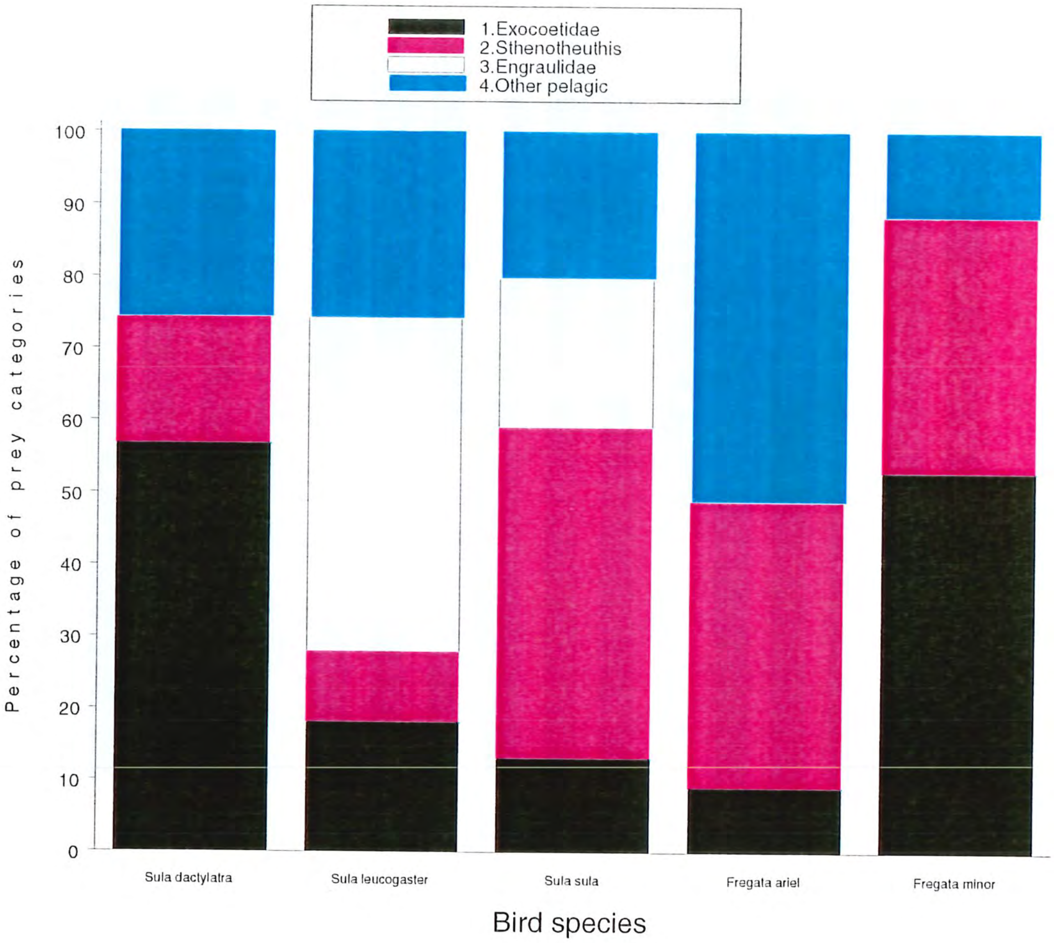


Figure 6.10 Proportions of four prey categories in the diets of seabirds from North–east Herald Cay, Coral Sea.

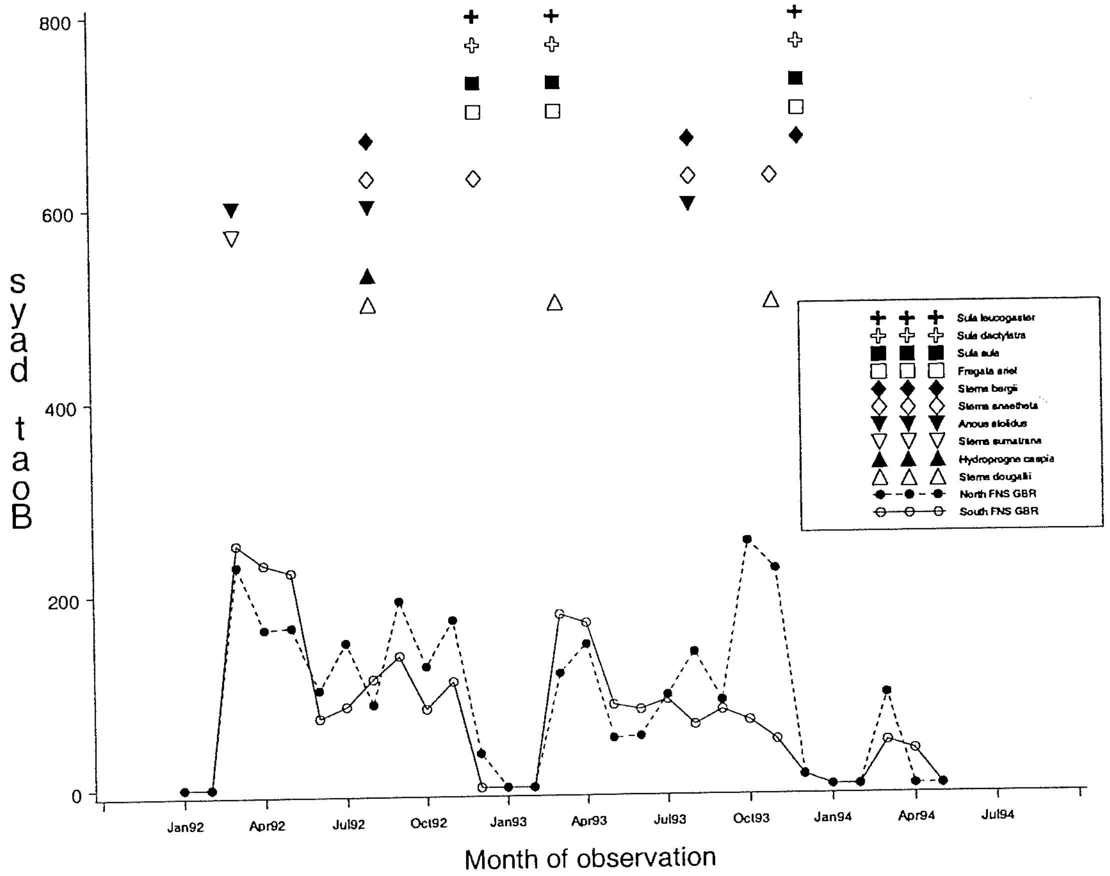


Figure 6.11 Prawn trawling effort and seabird breeding times in the Far Northern Section.

Prawn trawling effort North (●) and south (O) of the closed zone; breeding records for ten species are plotted above the prawn trawling effort.

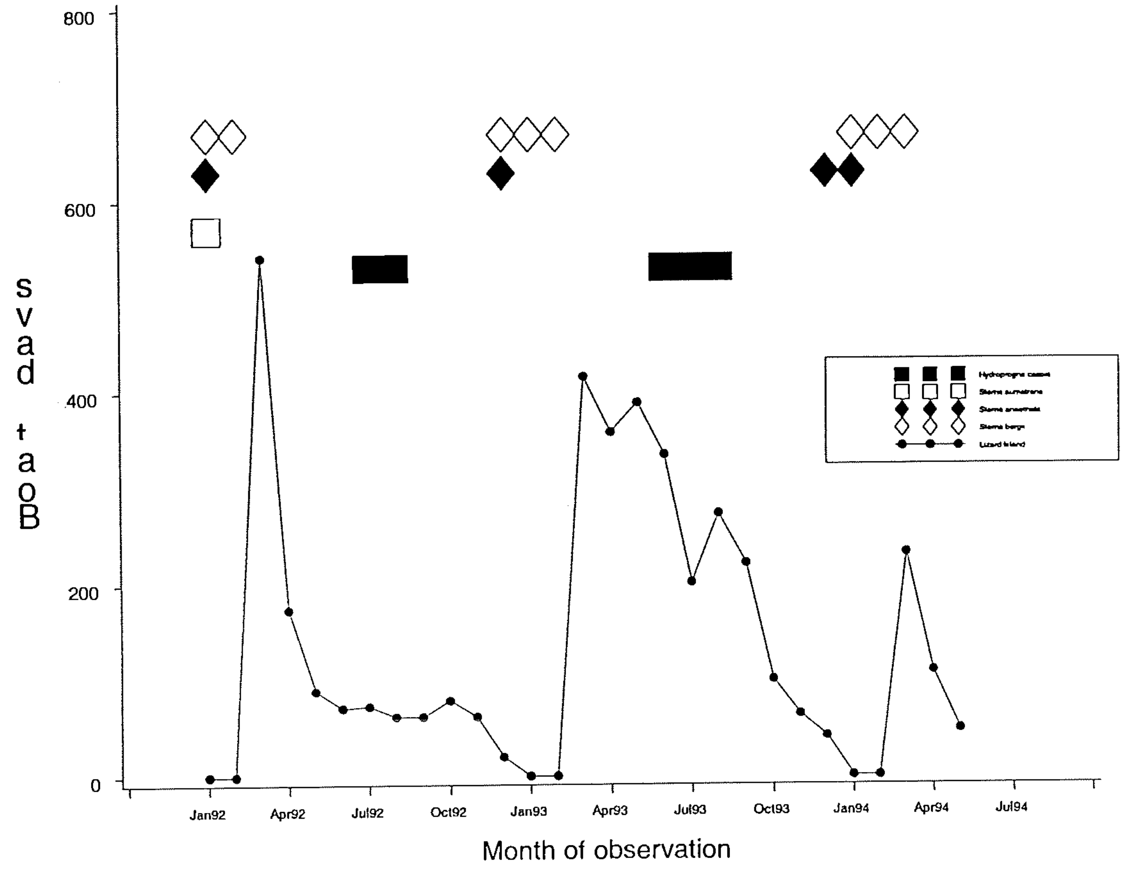


Figure 6.12 Prawn trawling effort and seabird breeding times in the Lizard Island area.

Solid line (●) indicates prawn trawling effort; Nesting periods for four species are plotted above the prawn trawling effort

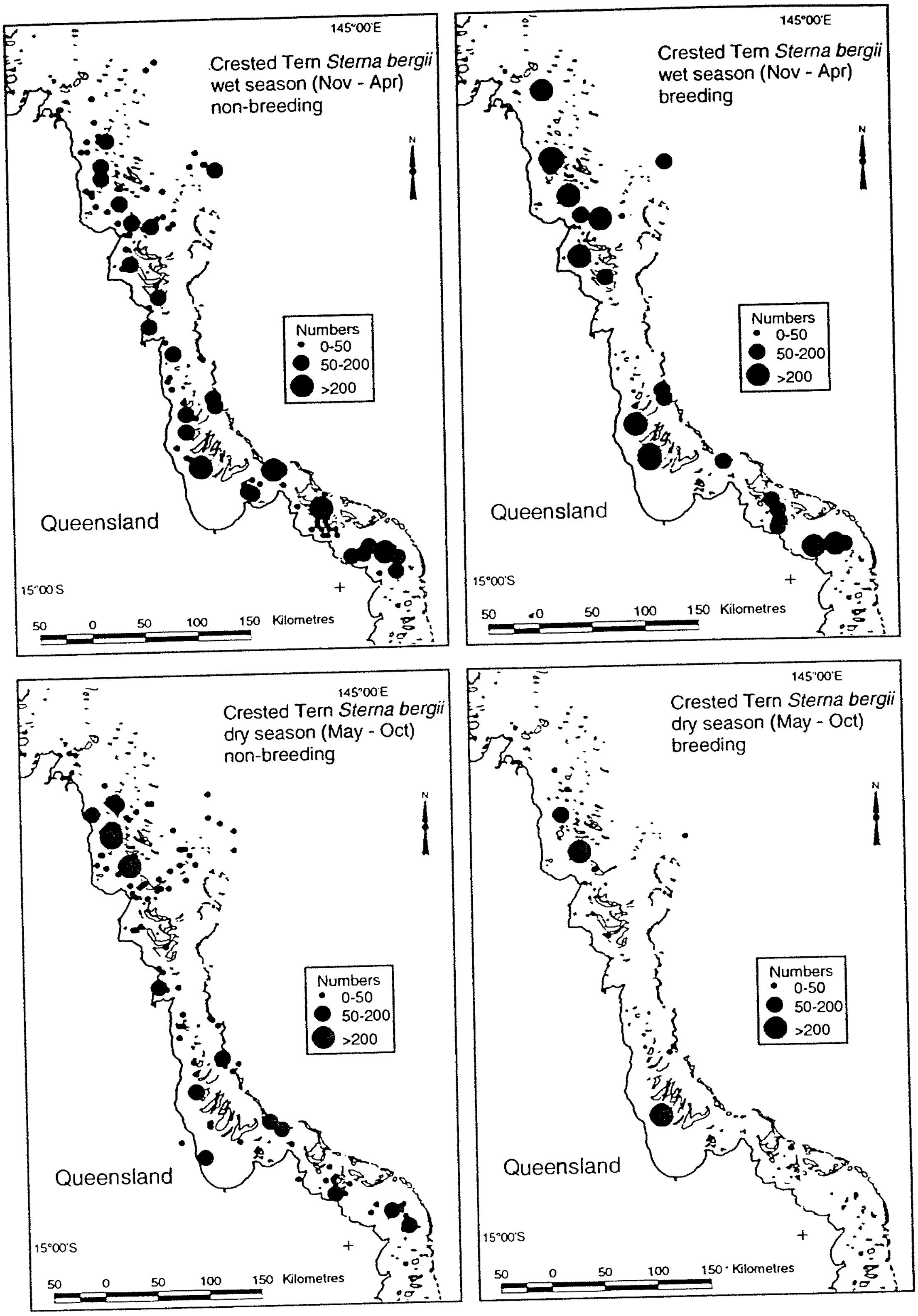


Figure 6.13 Distribution and abundance of Crested Terns in the Far Northern Great Barrier Reef region.

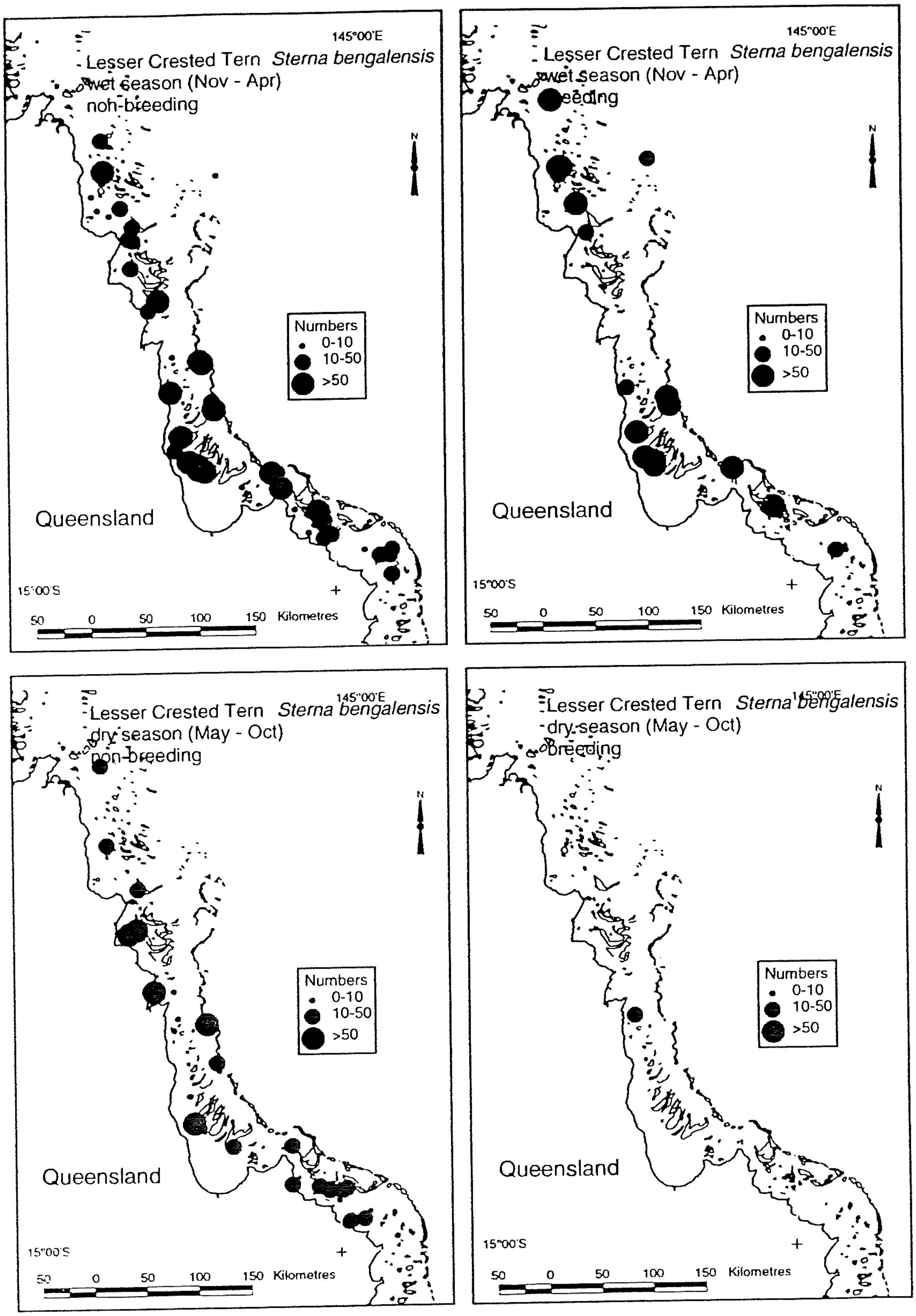


Figure 6.14 Distribution and abundance of Lesser Crested Terns in the Far Northern Great Barrier Reef region.

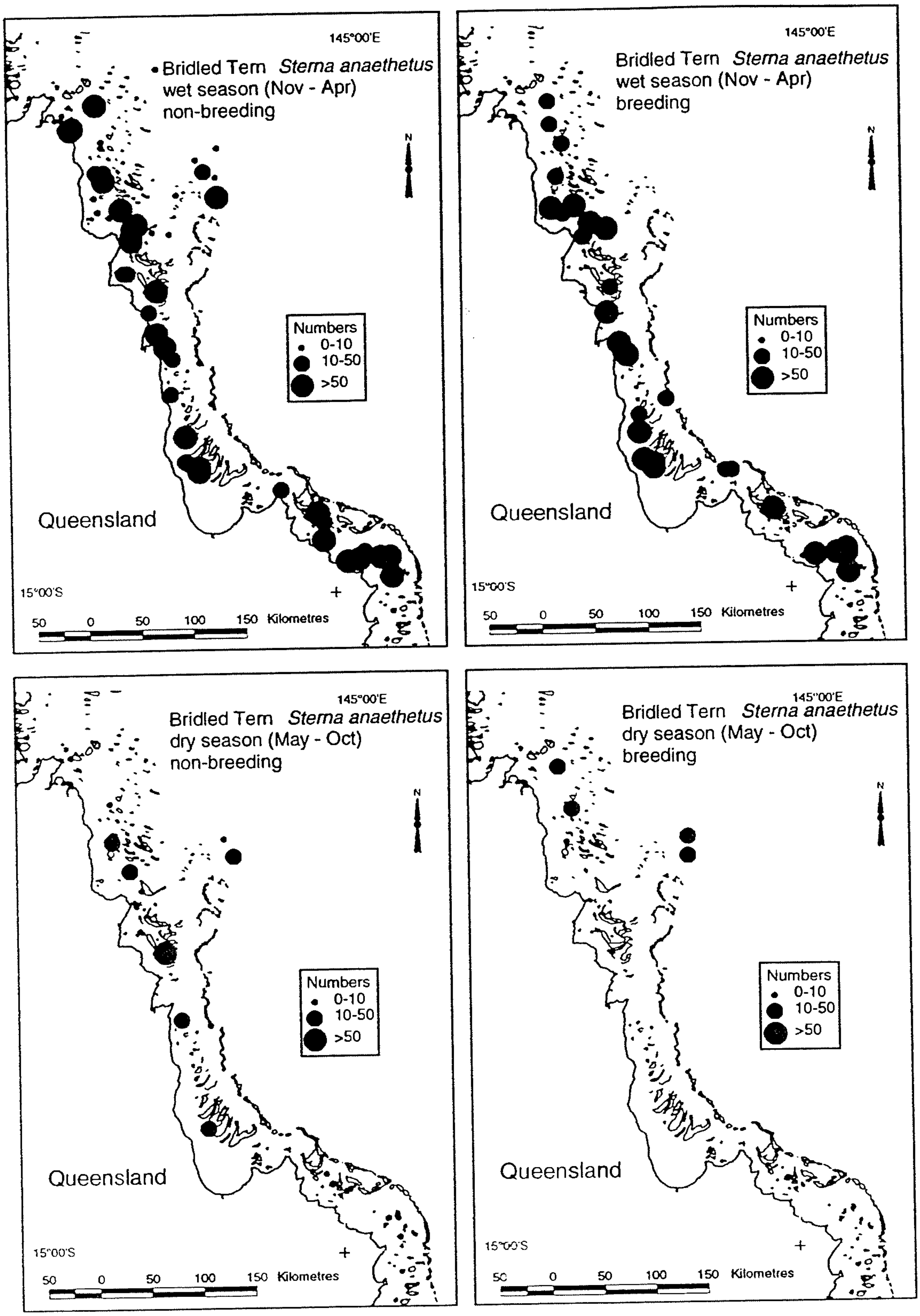


Figure 6.15 Distribution and abundance of Bridled Terns in the Far Northern Great Barrier Reef region.

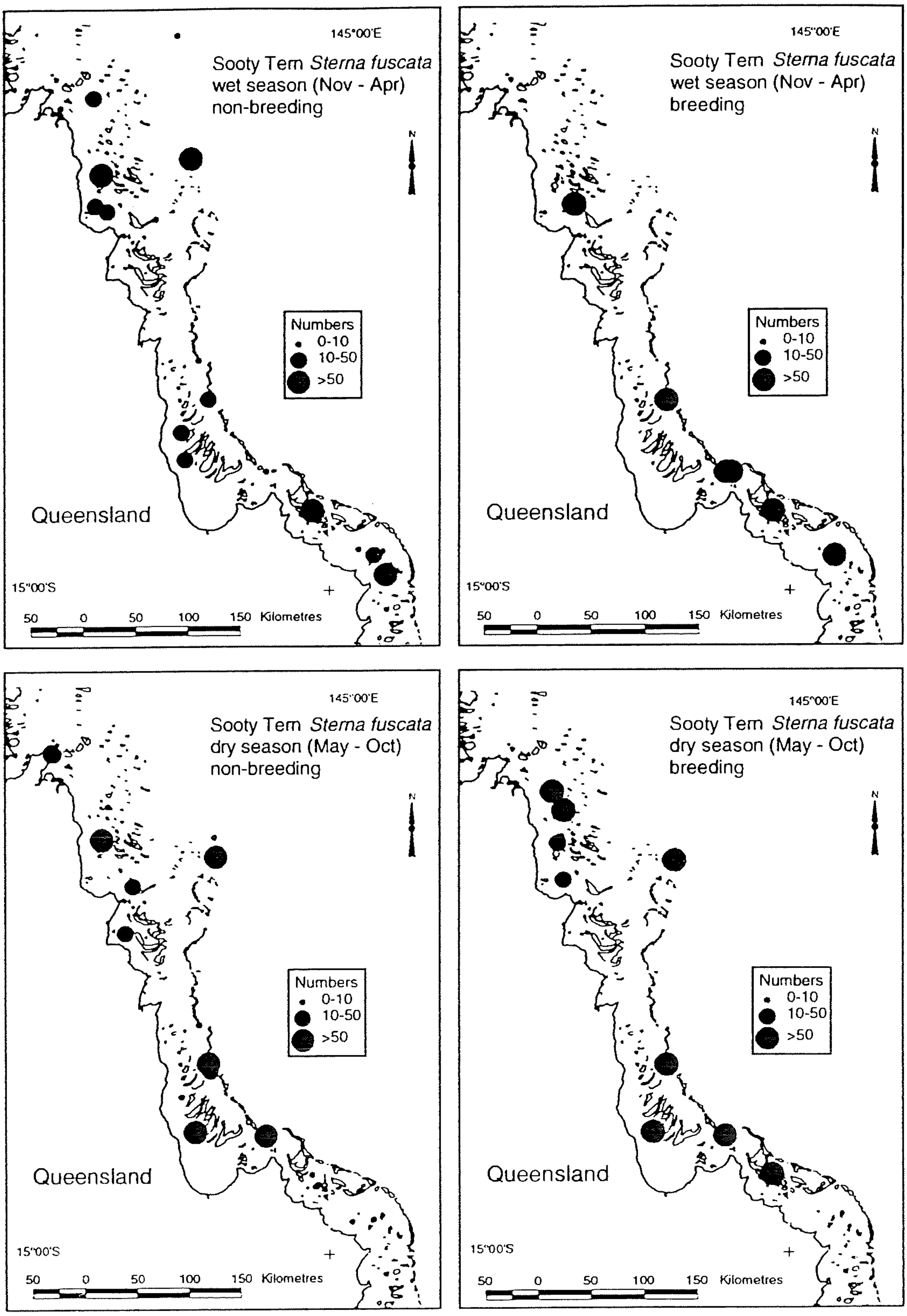


Figure 6.16 Distribution and abundance of Sooty Terns in the Far Northern Great Barrier Reef region.

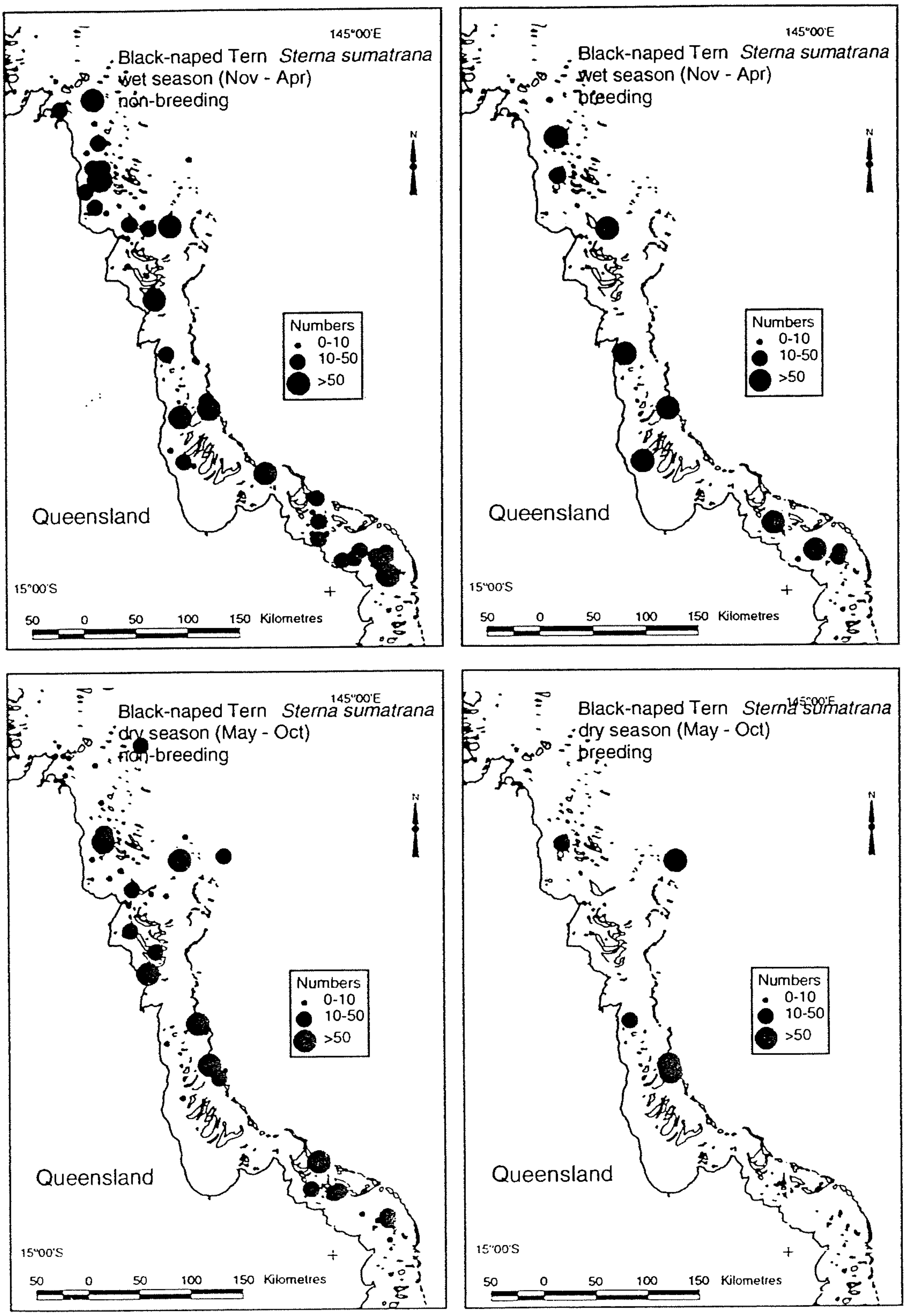


Figure 6.17 Distribution and abundance of Black-Naped Terns in the Far Northern Great Barrier Reef region.

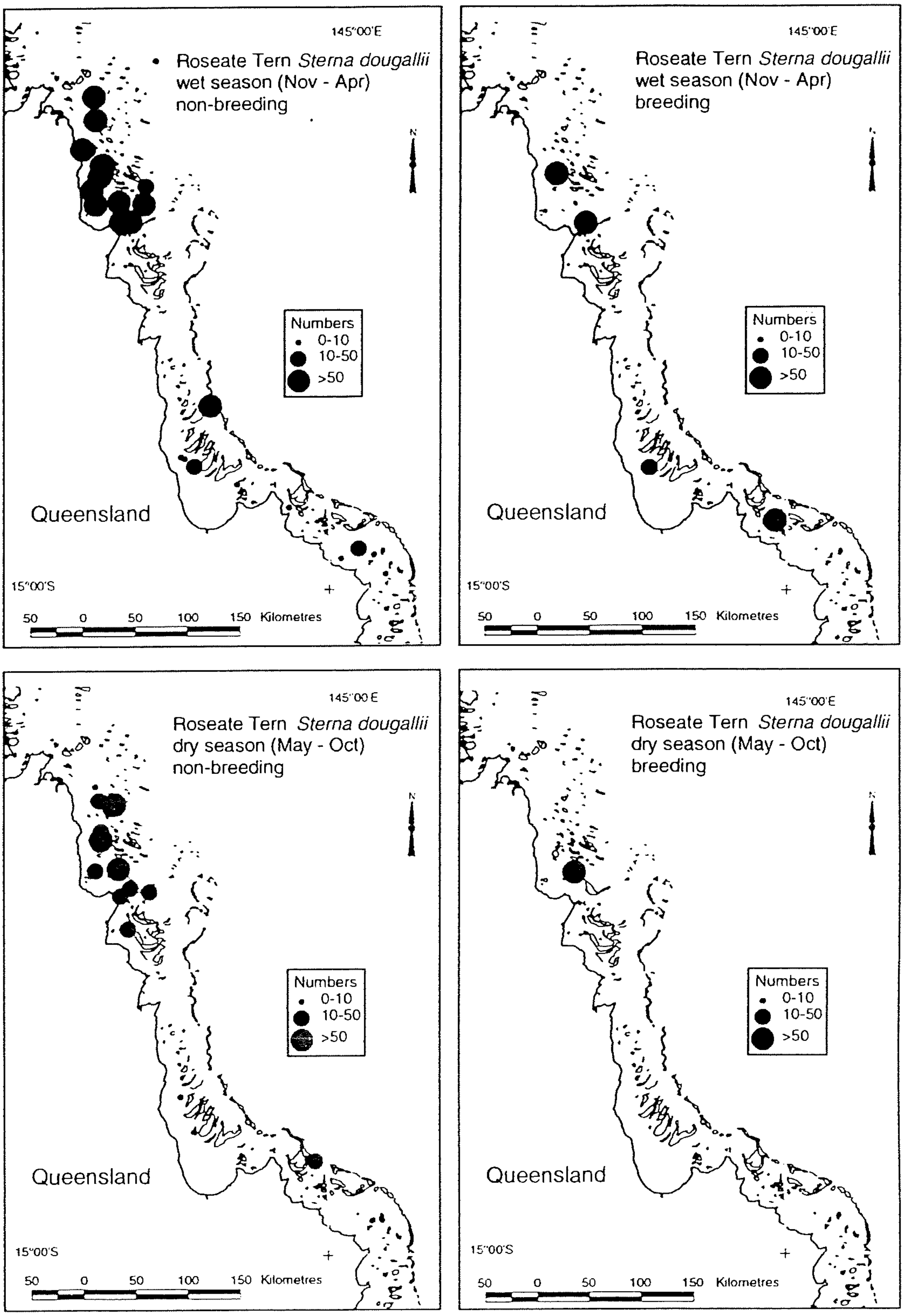


Figure 6.18 Distribution and abundance of Roseate Terns in the Far Northern Great Barrier Reef region.

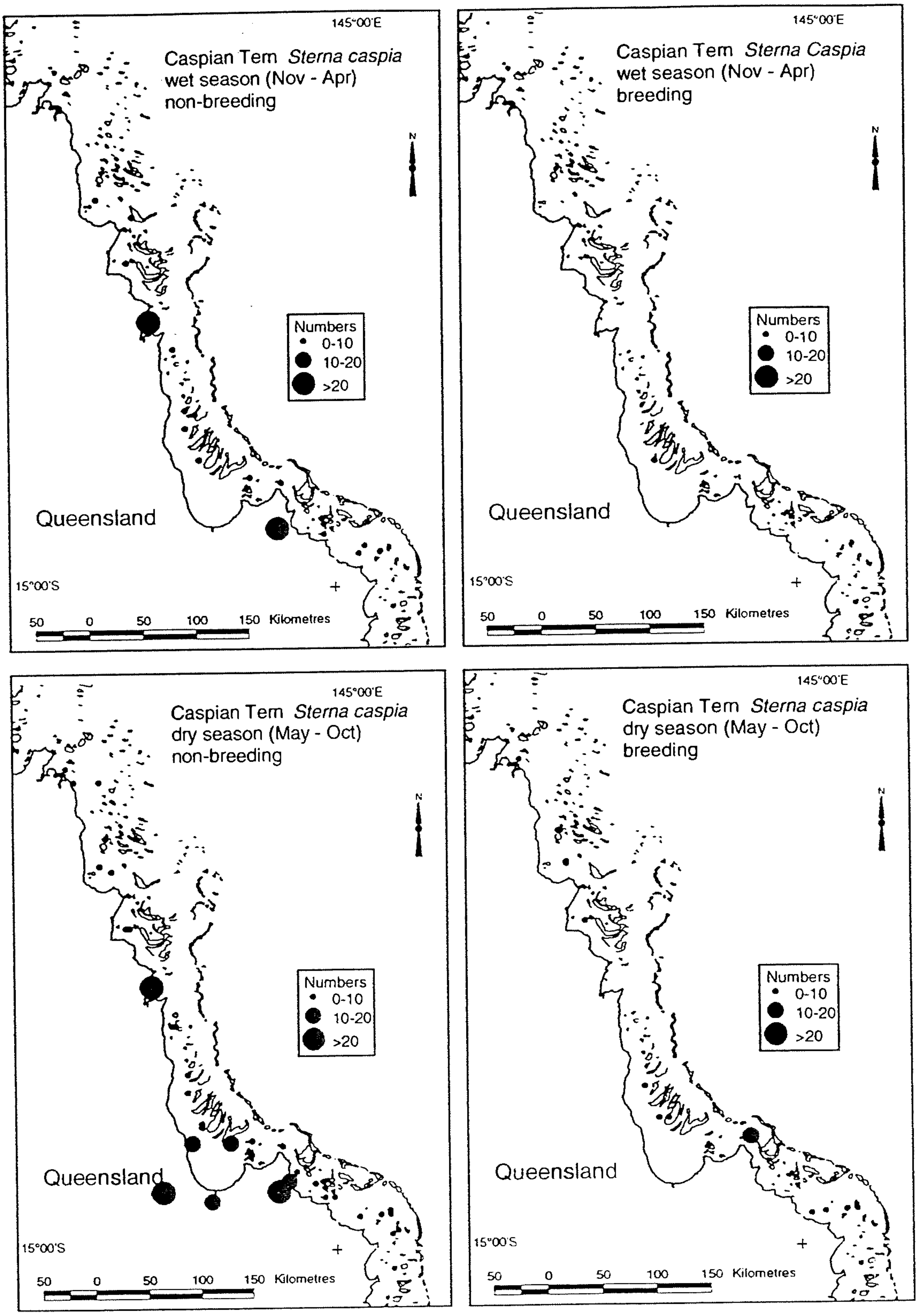


Figure 6.19 Distribution and abundance of Caspian Terns in the Far Northern Great Barrier Reef region.

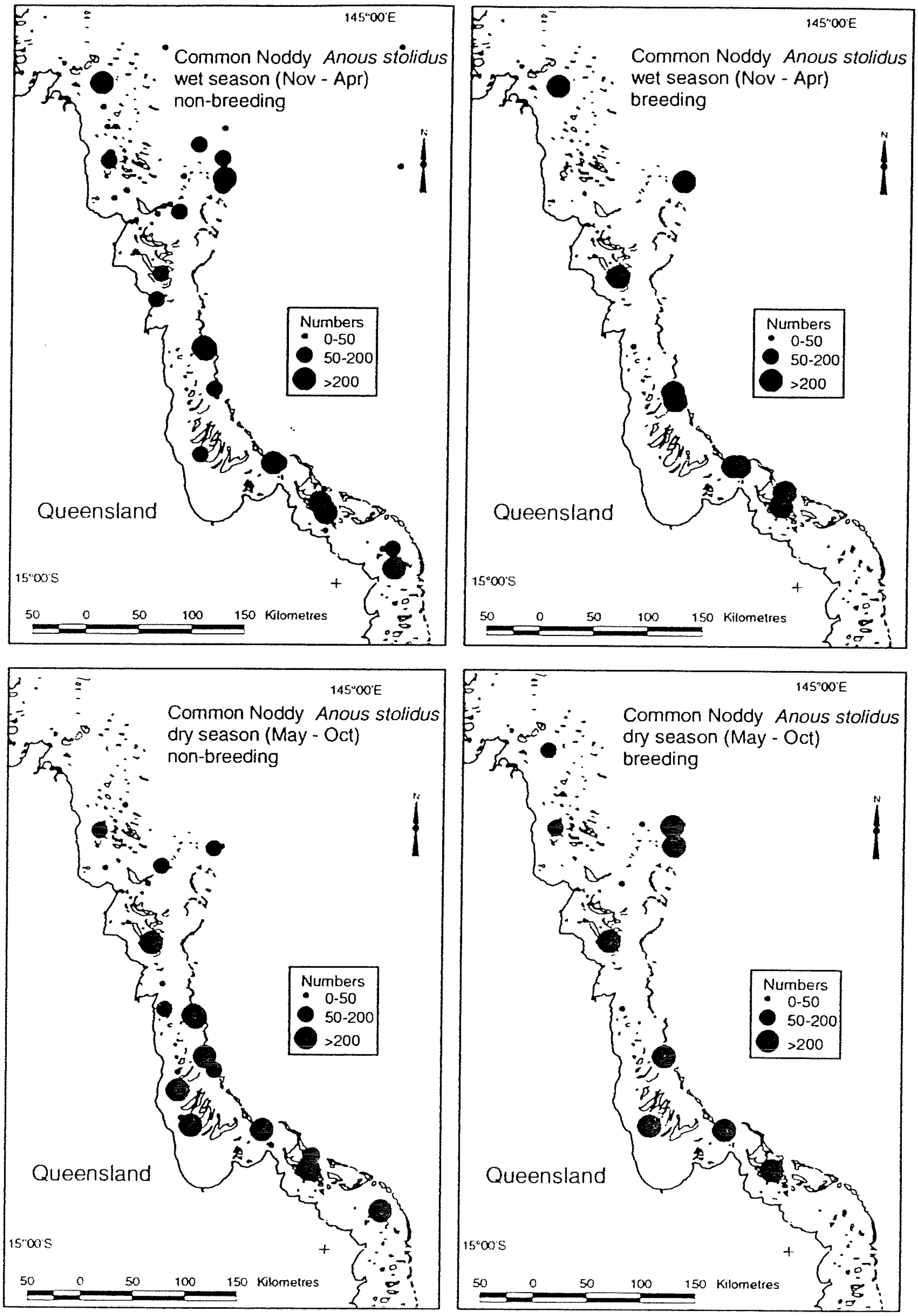


Figure 6.20 Distribution and abundance of Common Noddies in the Far Northern Great Barrier Reef region.

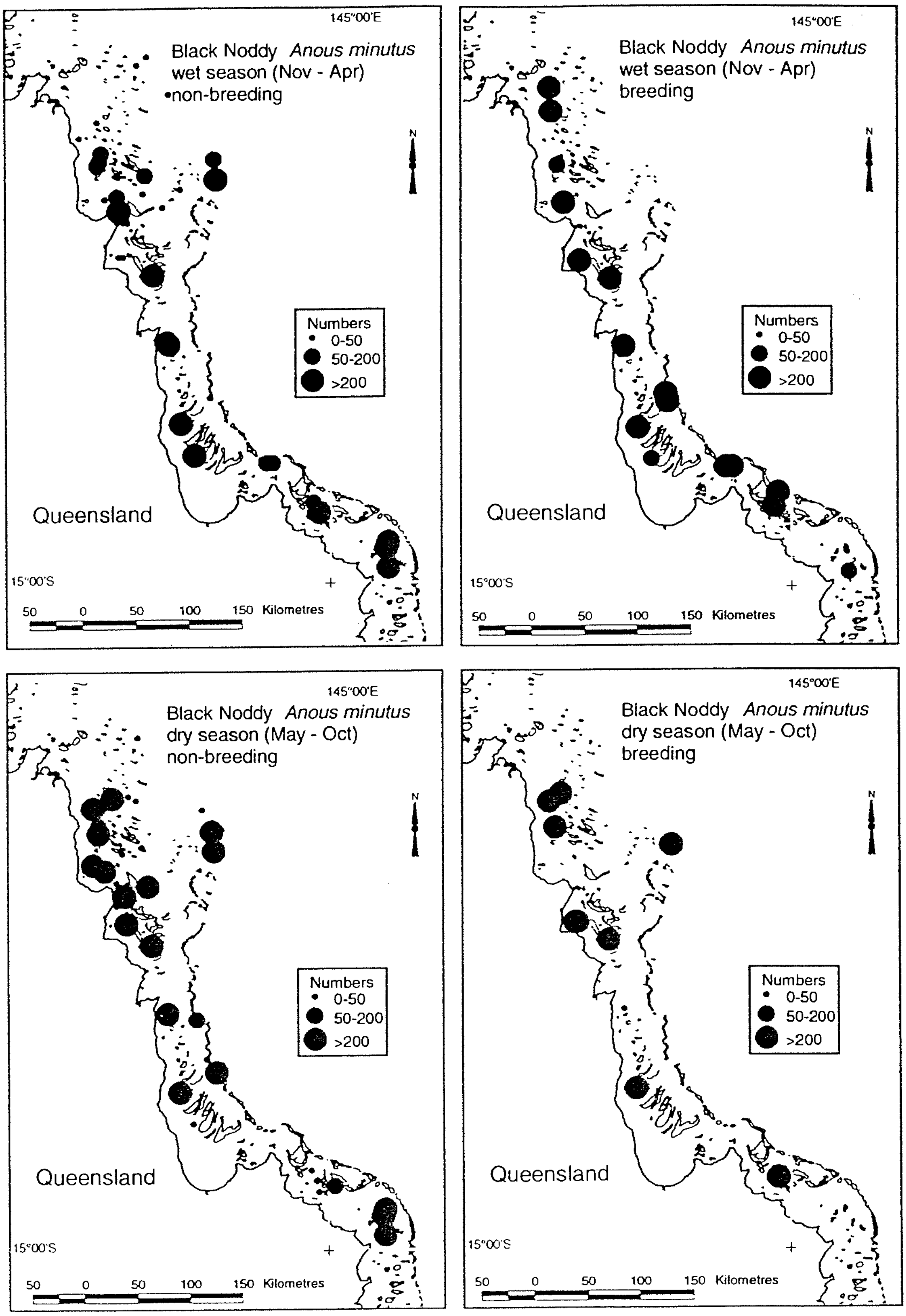


Figure 6.21 Distribution and abundance of Black Noddies in the Far Northern Great Barrier Reef region.

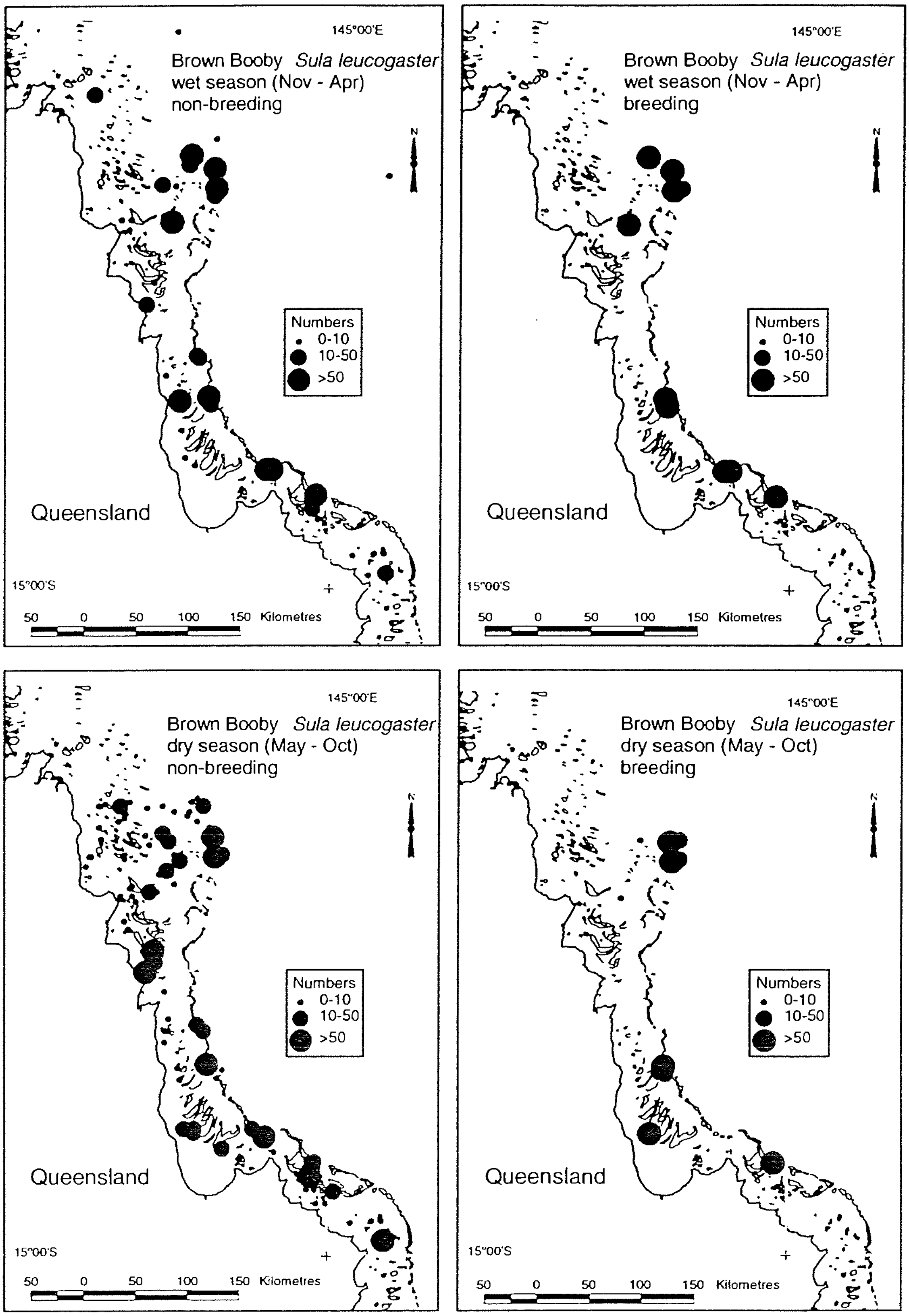


Figure 6.22 Distribution and abundance of Brown Boobies in the Far Northern Great Barrier Reef region.

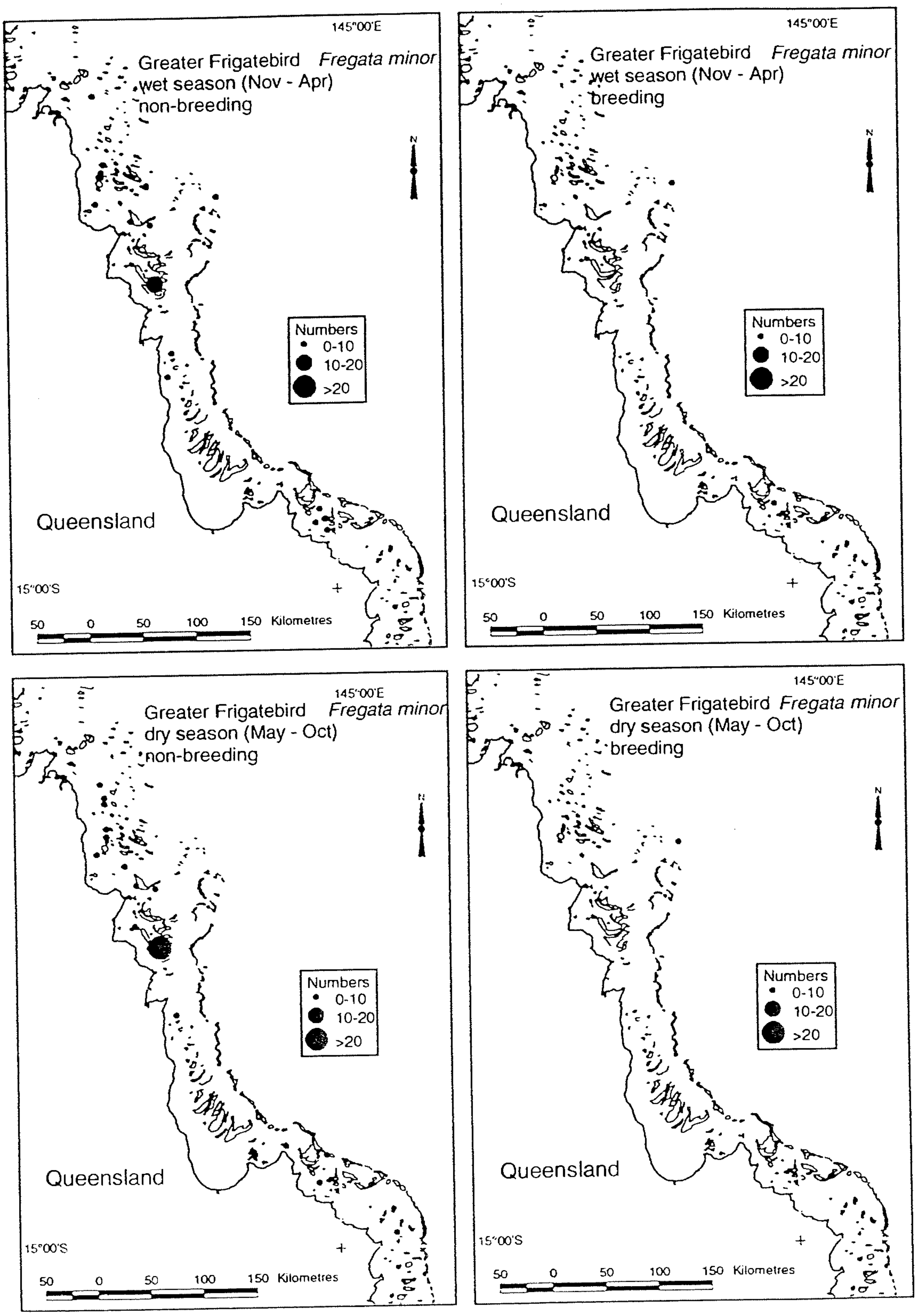


Figure 6.23 Distribution and abundance of Greater Frigatebirds in the Far Northern Great Barrier Reef region.

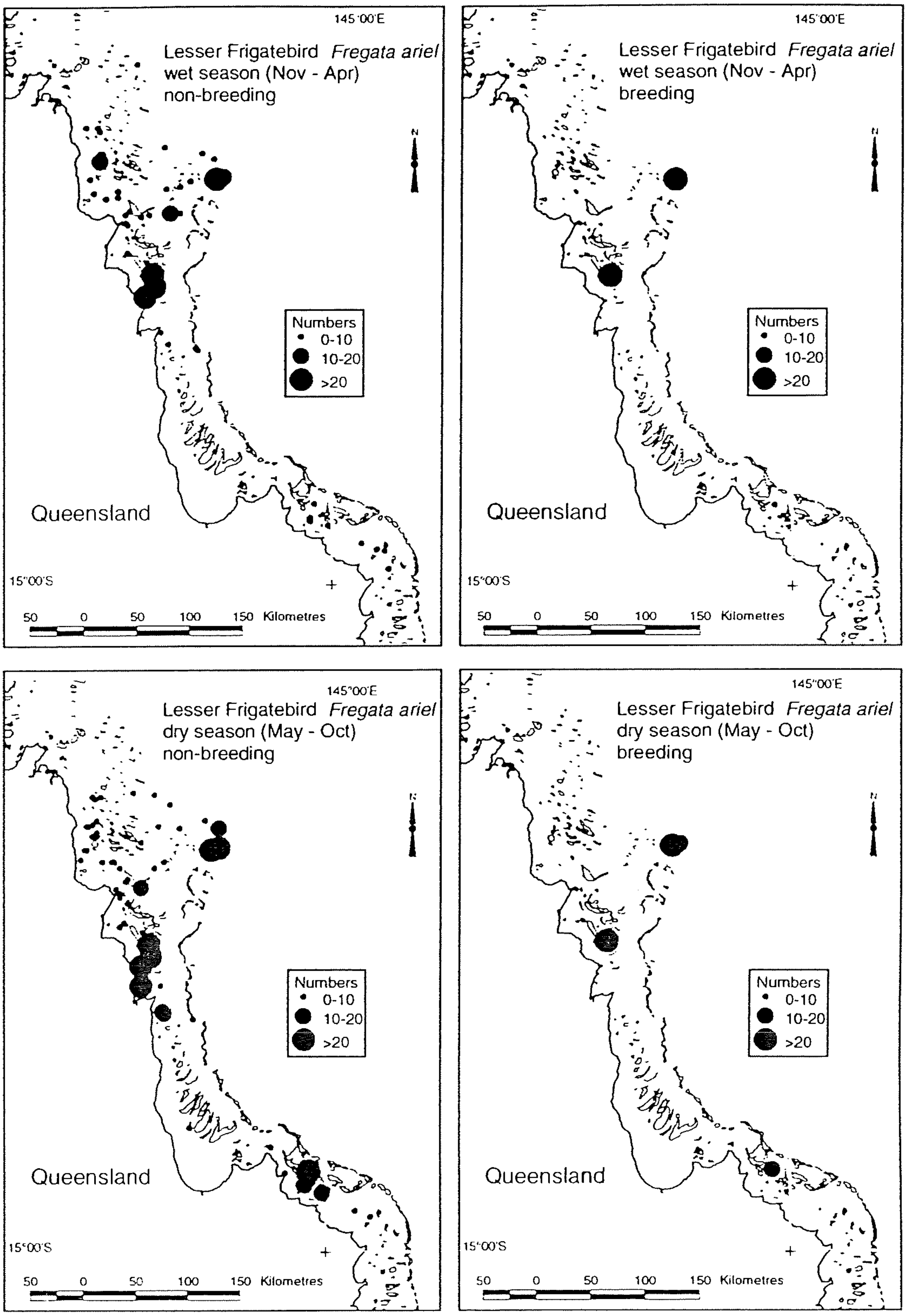


Figure 6.24 Distribution and abundance of Lesser Frigatebirds in the the Far Northern Great Barrier Reef region.

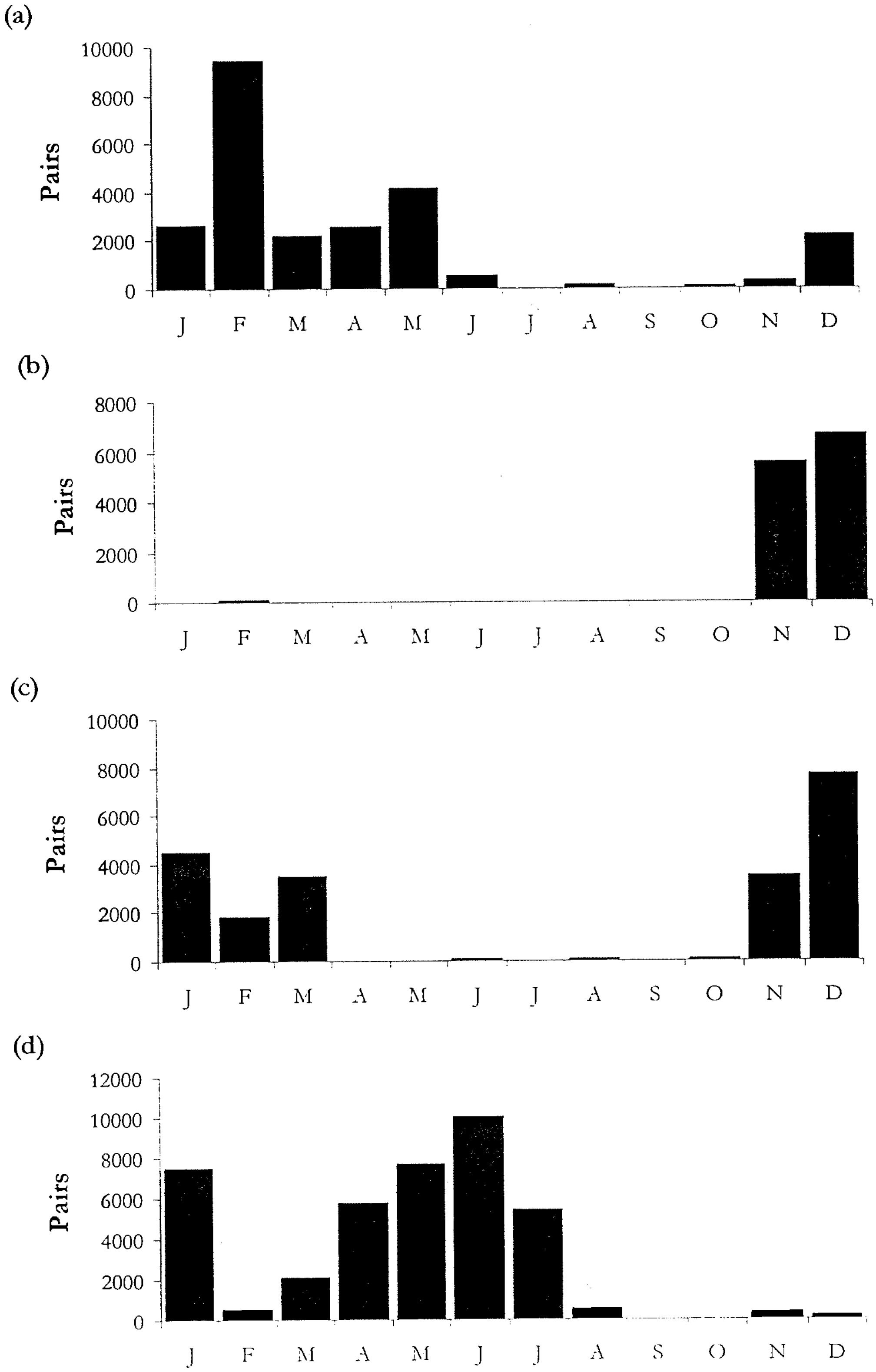


Figure 6.25 Breeding Records (number of pairs) per month for four species of seabirds on the Far Northern Great Barrier Reef, 1977 to 1996.

(a) Crested Tern; (b) Lesser Crested tern; (c) Bridled tern; (d) Sooty tern.

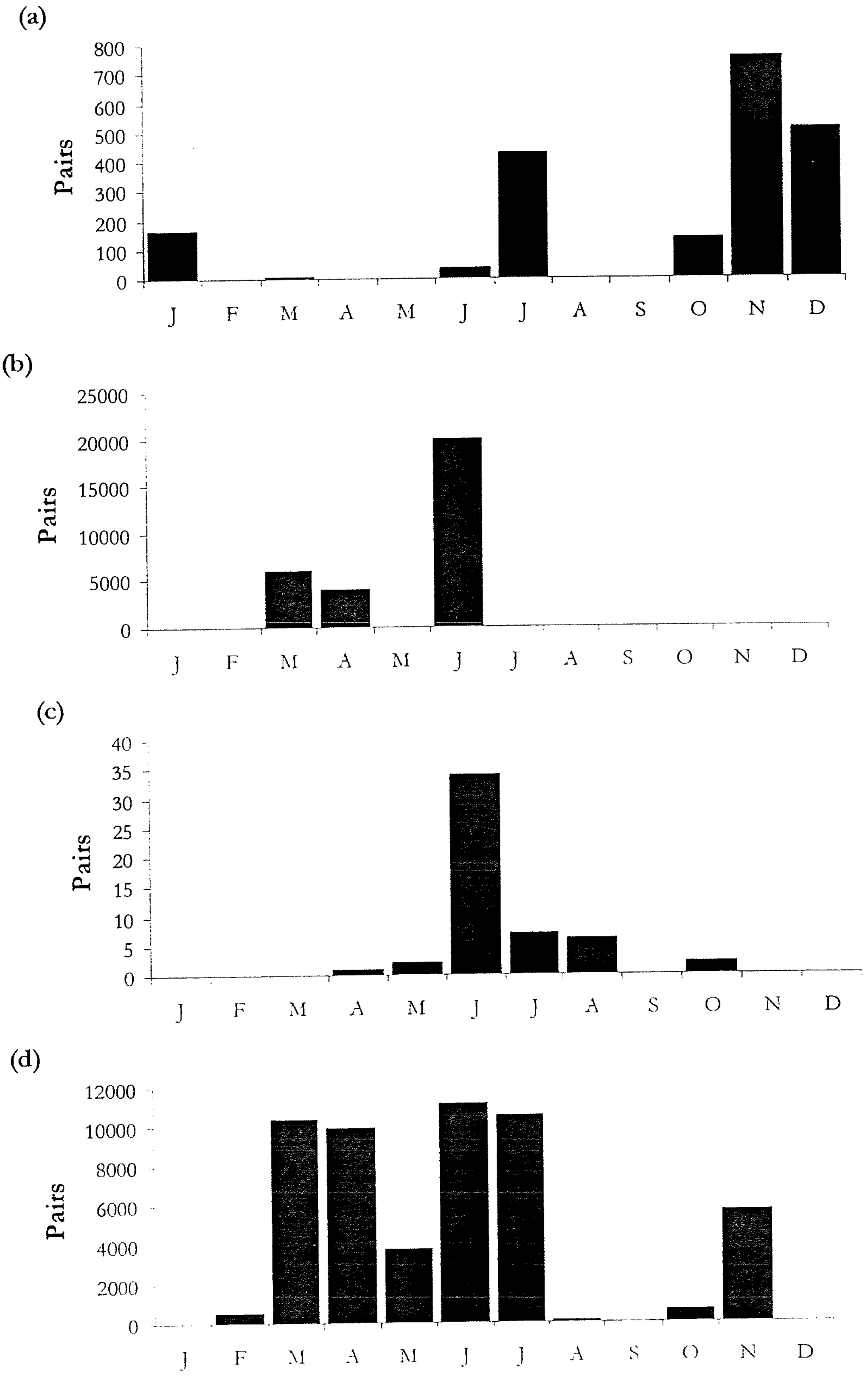


Figure 6.26 Breeding Records (number of pairs) per month for four species of seabirds on the Far Northern Great Barrier Reef, 1977 to 1996.

(a) Black-Naped Tern; (b) Roseate Tern; (c) Caspian Tern; (d) Lesser Frigate Bird.

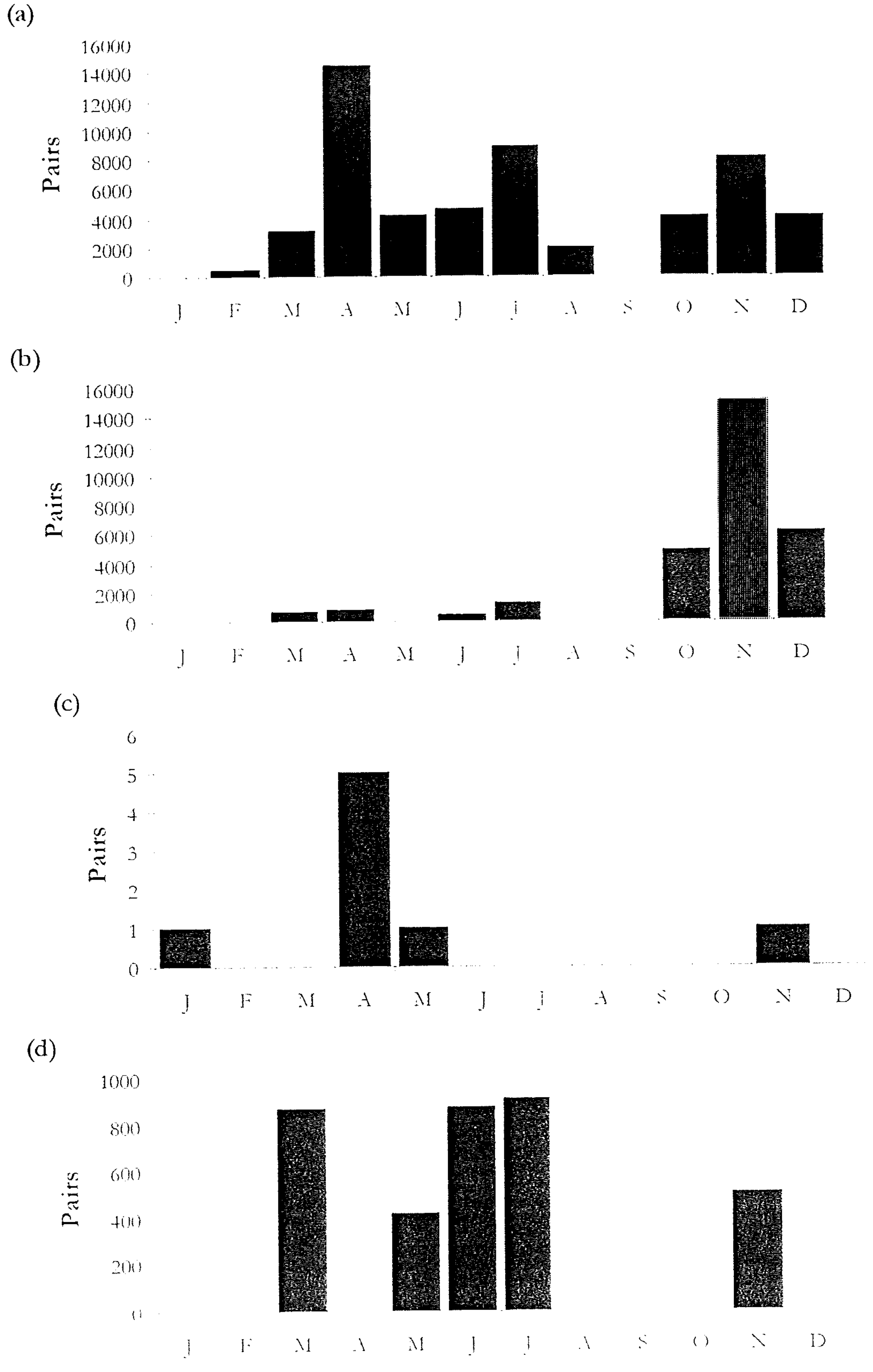
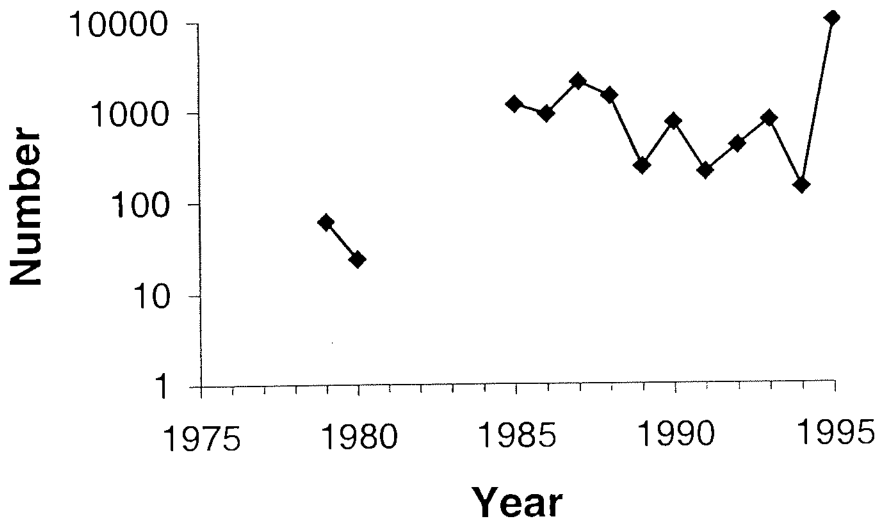
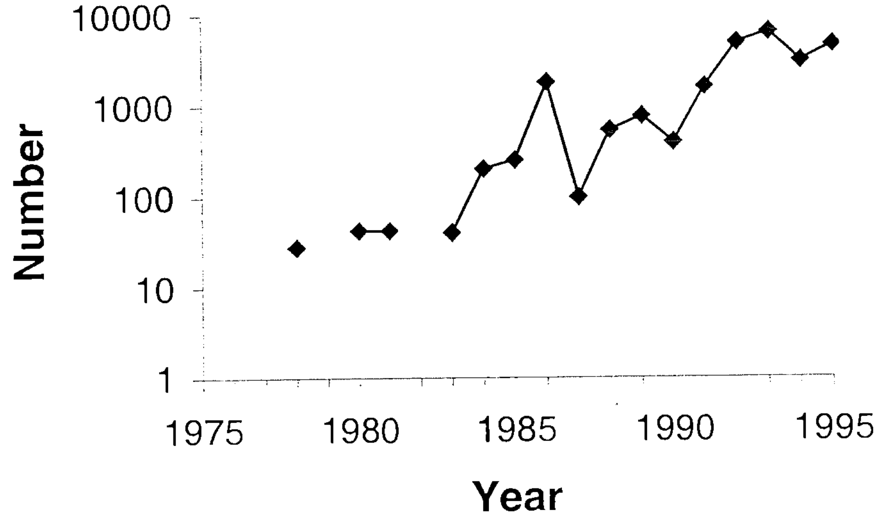


Figure 6.27 Breeding Records (number of pairs) per month for four species of seabirds on the Far Northern Great Barrier Reef, 1977 to 1996.

(a) Black Noddy; (b) Brown Booby; (c) Greater Frigate Bird; (d) Lesser Frigate Bird.

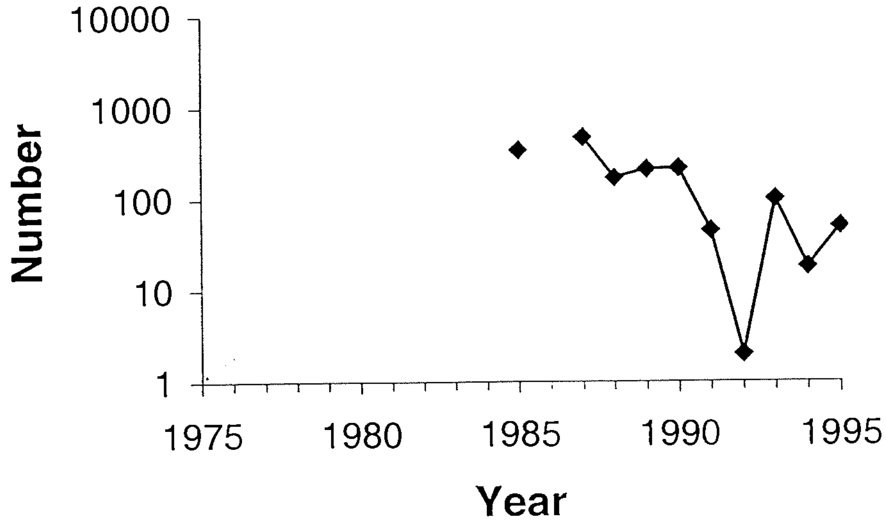


(a)

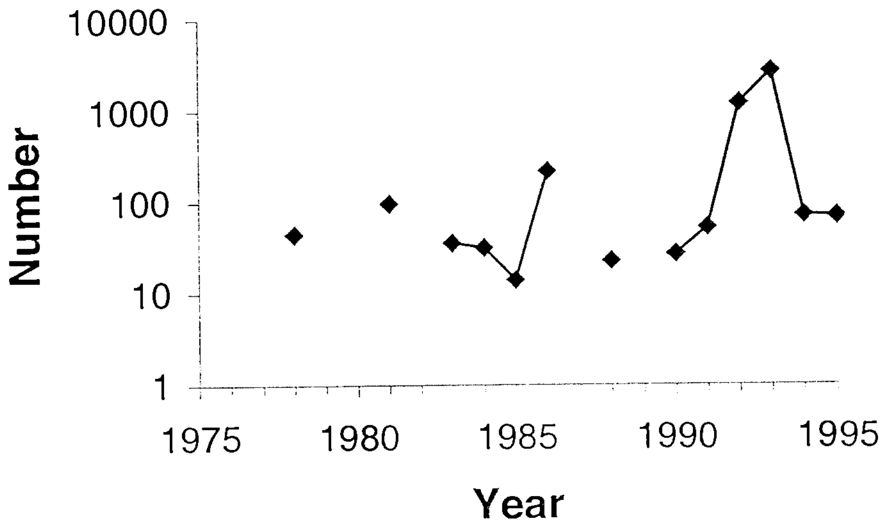


(b)

Figure 6.28 Changes in the abundance of Crested Terns in the Cross-Shelf Closure and Lizard Island area from 1977 to 1996.

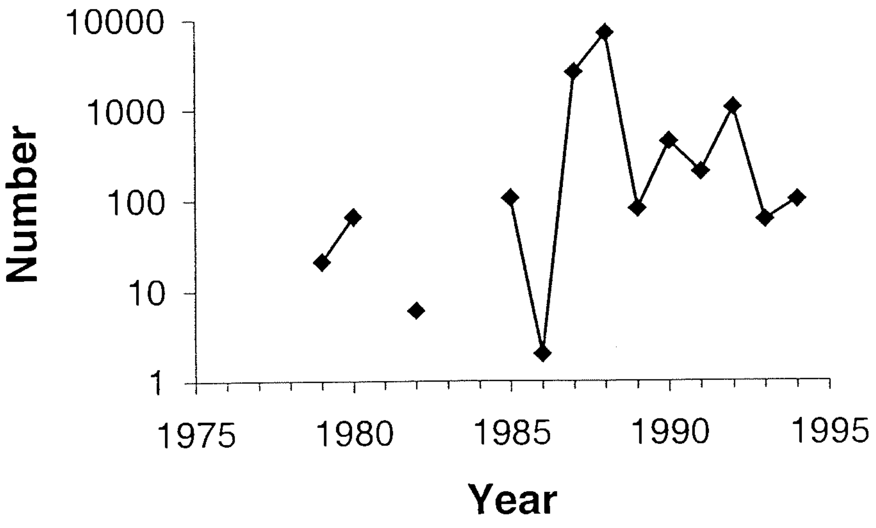


(a)

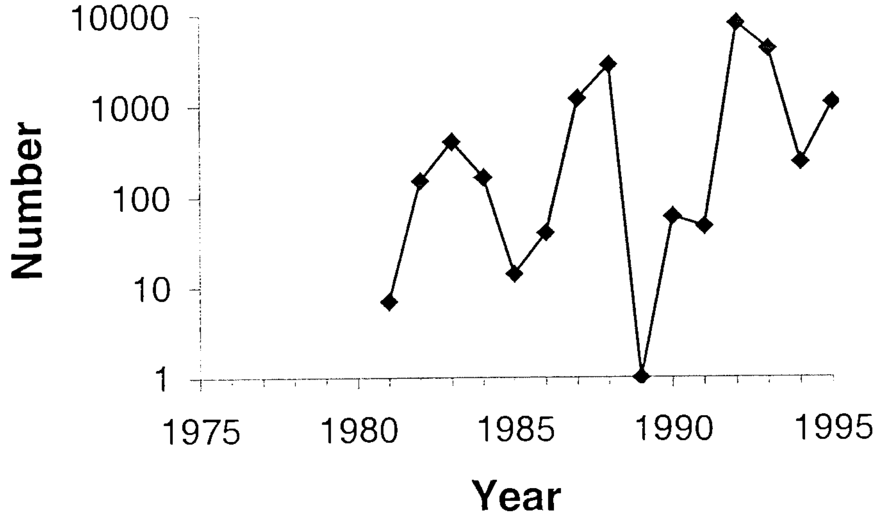


(b)

Figure 6.29 Changes in the abundance of Lesser Crested Terns in the Cross-Shelf Closure and Lizard Island area from 1977 to 1996.

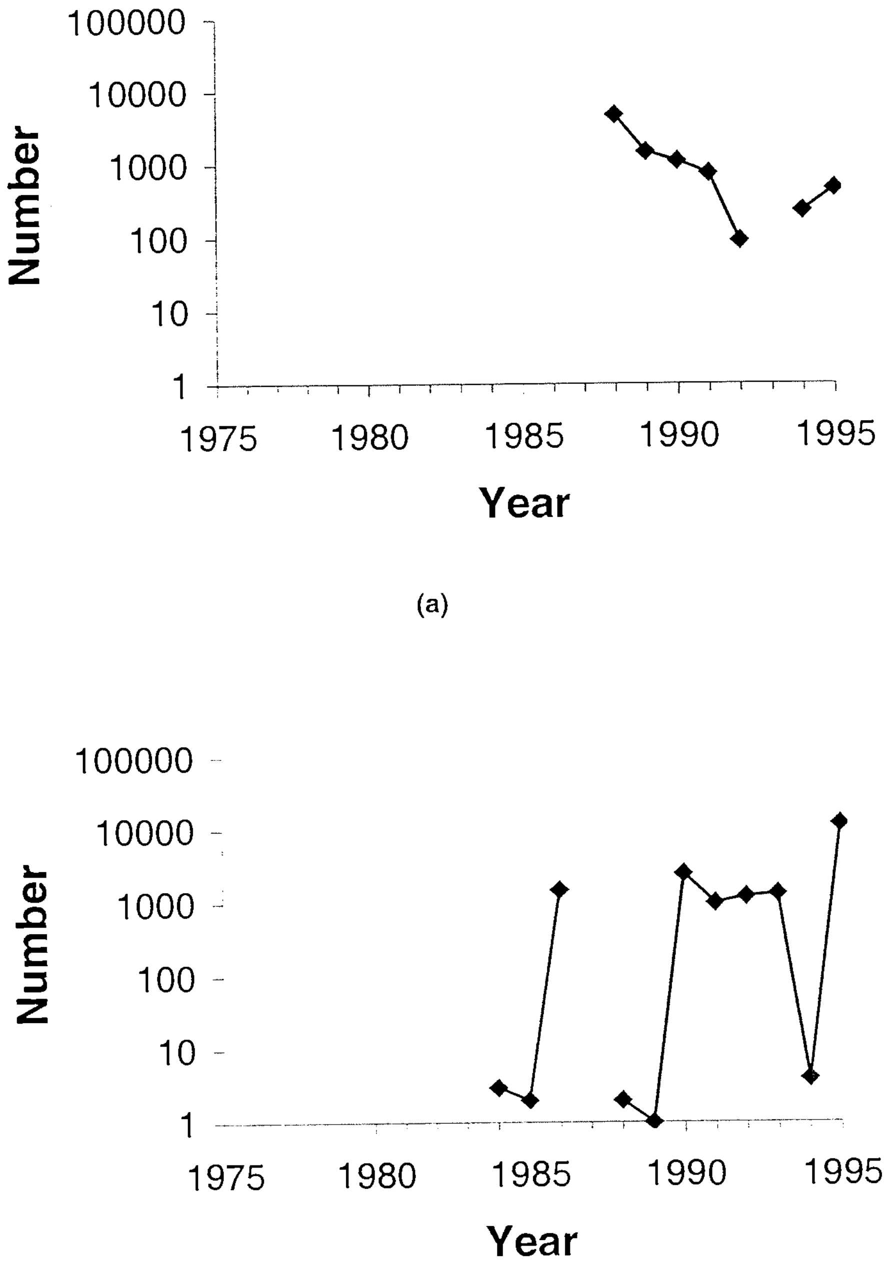


(a)



(b)

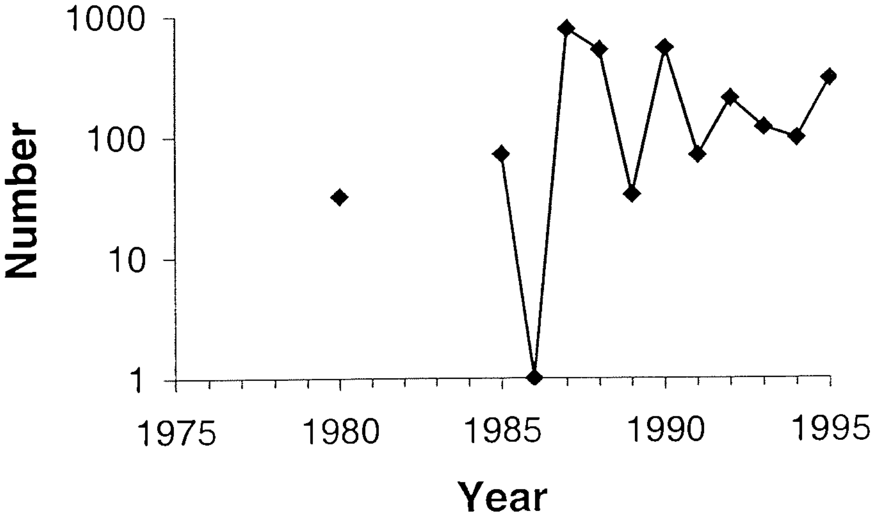
Figure 6.30 Changes in the abundance of Bridled Terns in the Cross-Shelf Closure and Lizard Island area from 1977 to 1996.



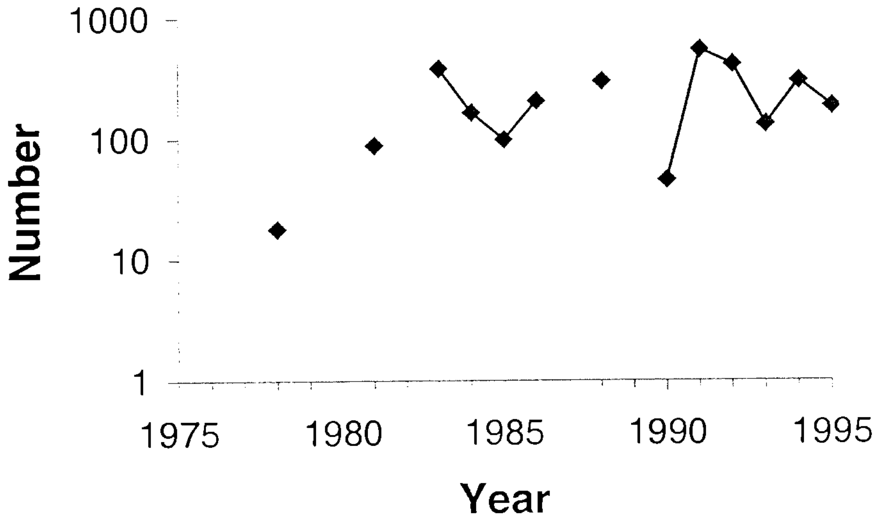
(a)

(b)

Figure 6.31 Changes in the abundance of Sooty Terns in the Cross-Shelf Closure and Lizard Island area from 1977 to 1996.

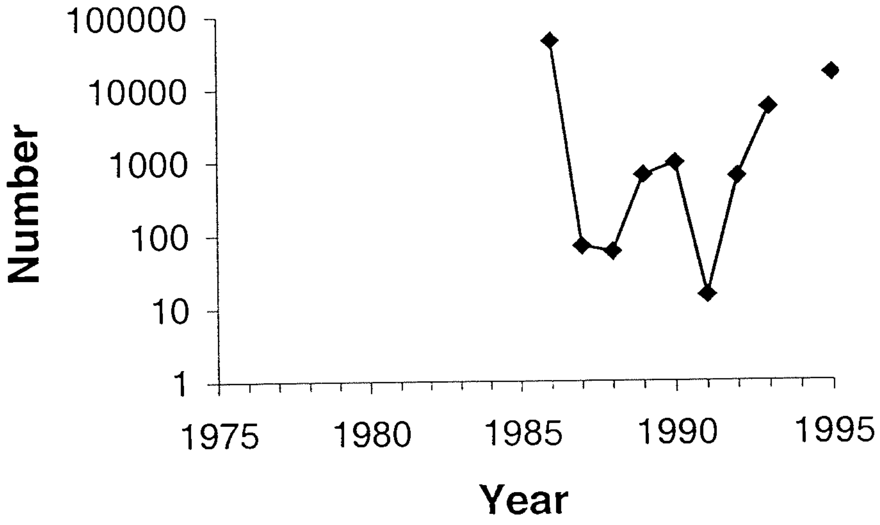


(a)

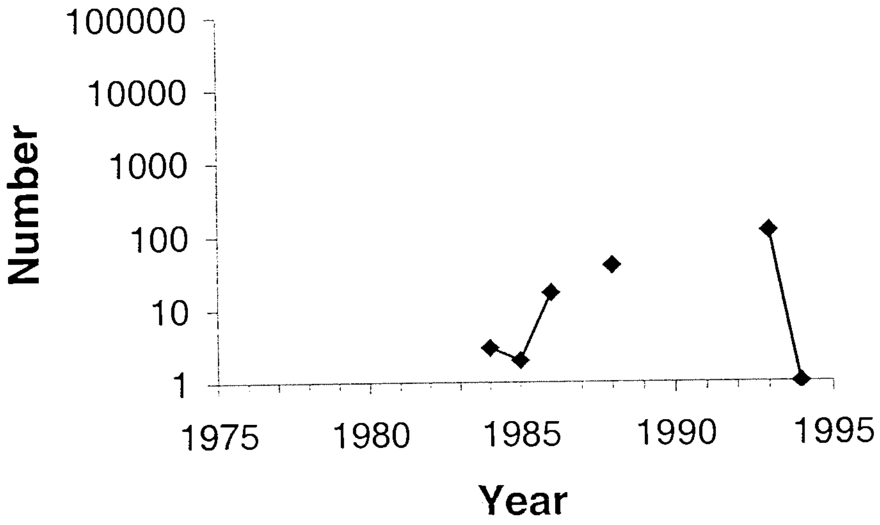


(b)

Figure 6.32 Changes in the abundance of Black-Naped Terns in the Cross-Shelf Closure and Lizard Island area from 1977 to 1996.

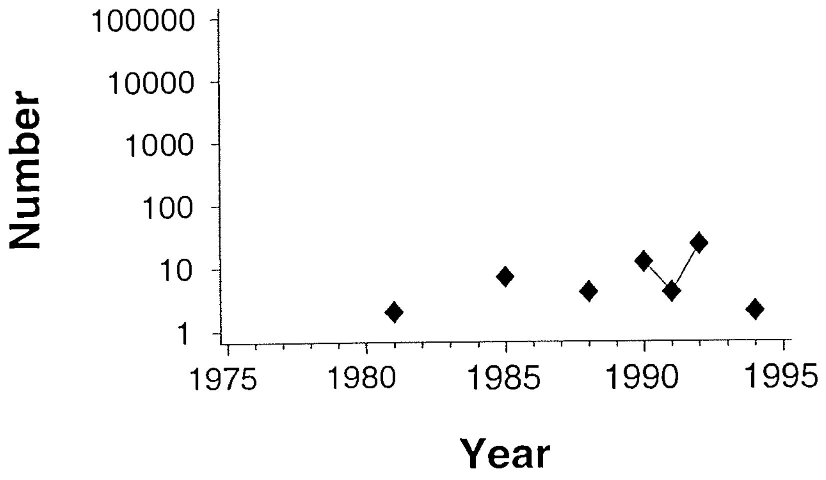


(a)



(b)

Figure 6.33 Changes in the abundance of Roseate Terns in the Cross-Shelf Closure and Lizard Island area from 1977 to 1996.



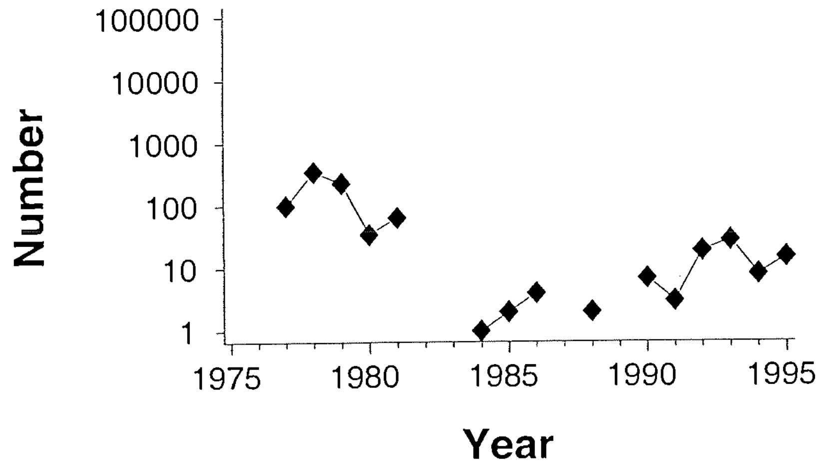
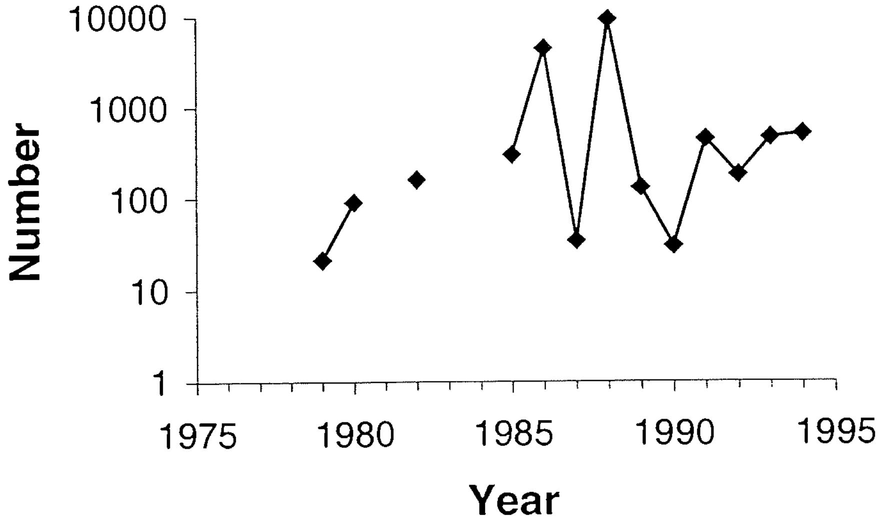
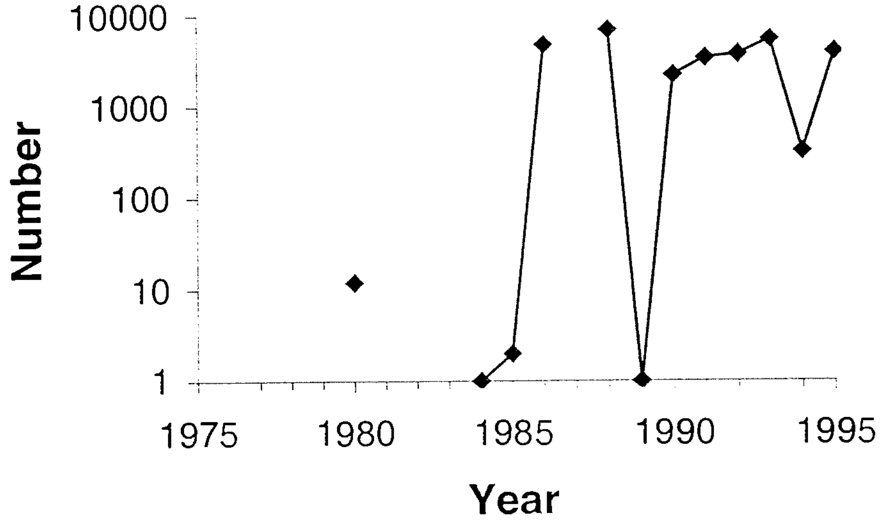


Figure 6.34 Changes in the abundance of Caspian Terns in the Cross-Shelf Closure and Lizard Island area from 1977 to 1996.

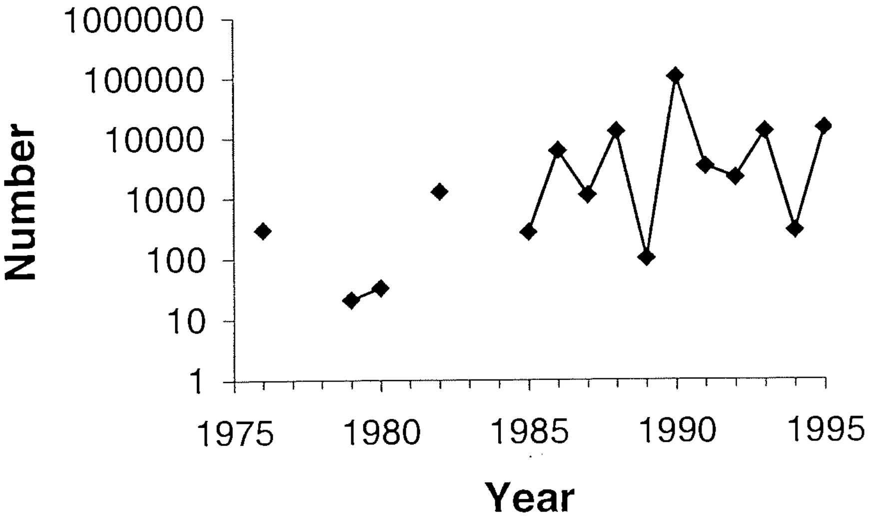


(a)

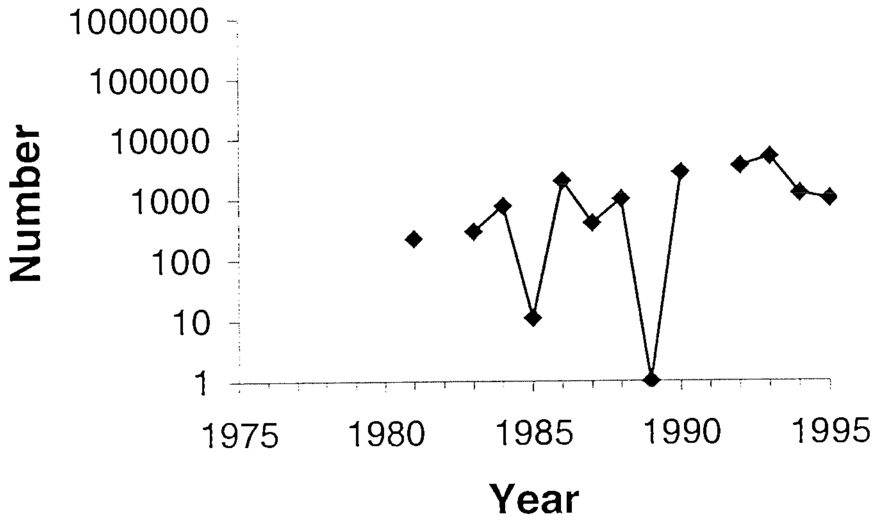


(b)

Figure 6.35 Changes in the abundance of Common Noddies in the Cross-Shelf Closure and Lizard Island area from 1977 to 1996.

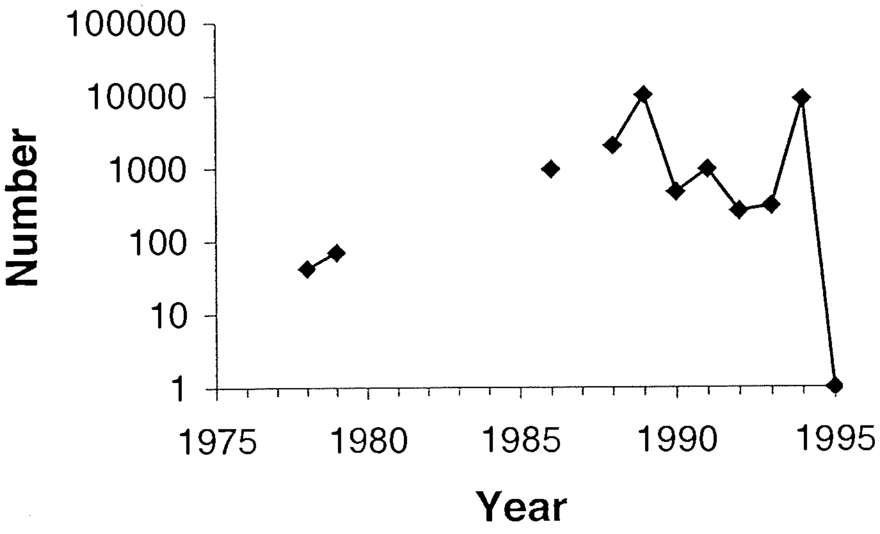


(a)

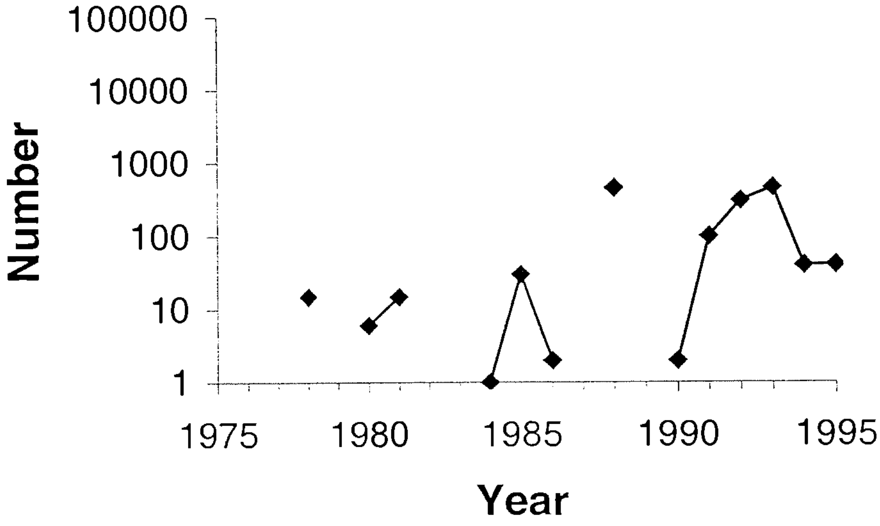


(b)

Figure 6.36 Changes in the abundance of Black Noddies in the Cross-Shelf Closure and Lizard Island area from 1977 to 1996.

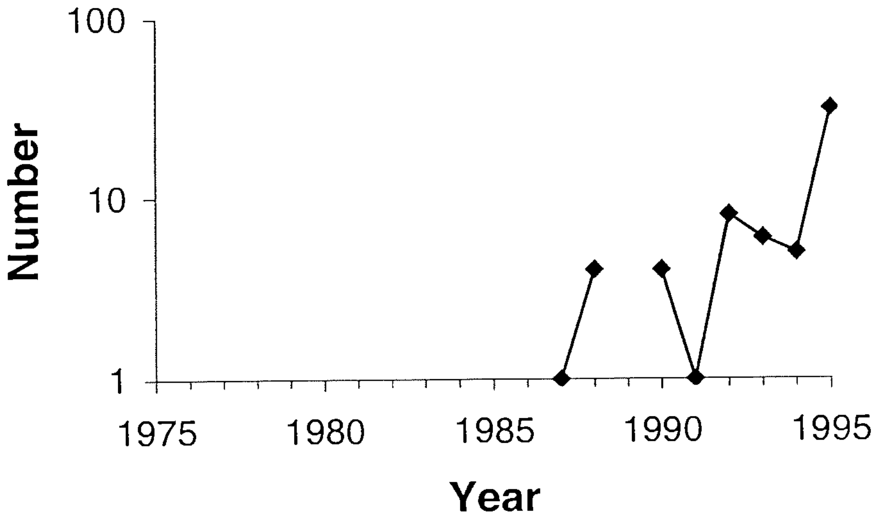


(a)

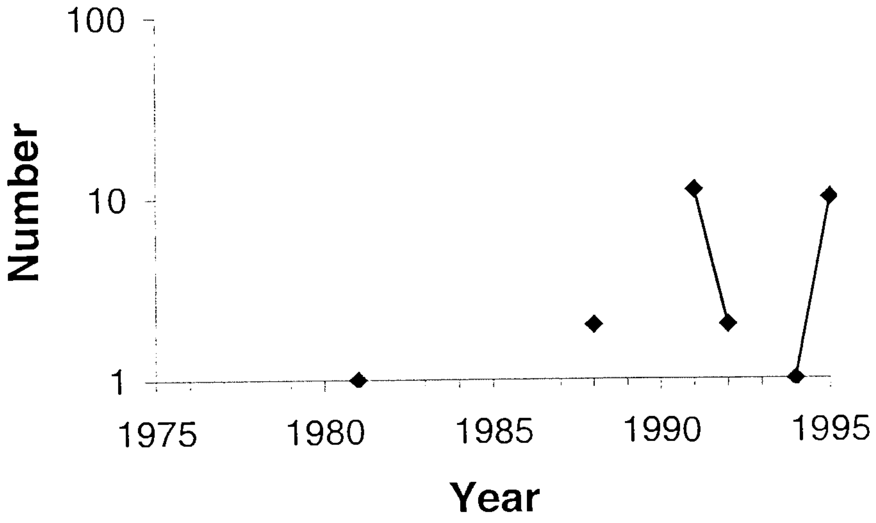


(b)

Figure 6.37 Changes in the abundance of Brown Boobies in the Cross-Shelf Closure and Lizard Island area from 1977 to 1996.

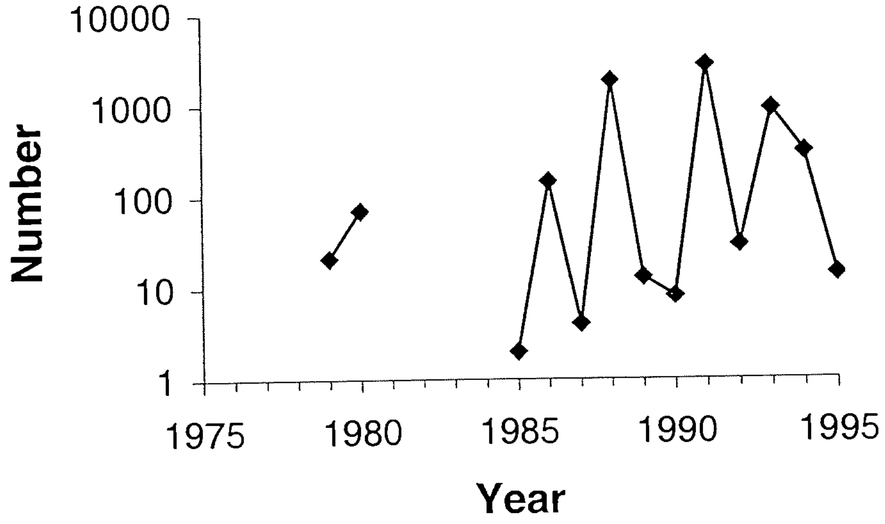


(a)

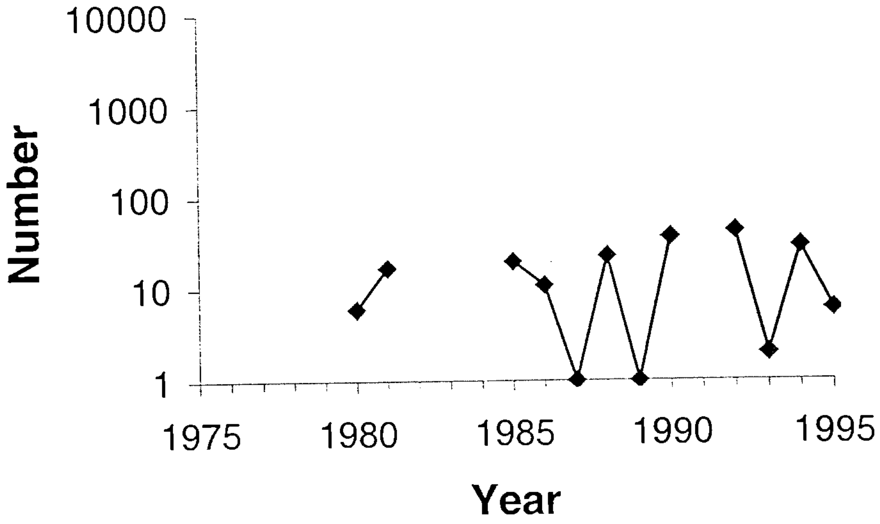


(b)

Figure 6.38 Changes in the abundance of Greater Frigate Birds in the Cross-Shelf Closure and Lizard Island area from 1977 to 1996.



(a)



(b)

Figure 6.39 Changes in the abundance of Lesser Frigate Birds in the Cross-Shelf Closure and Lizard Island area from 1977 to 1996.

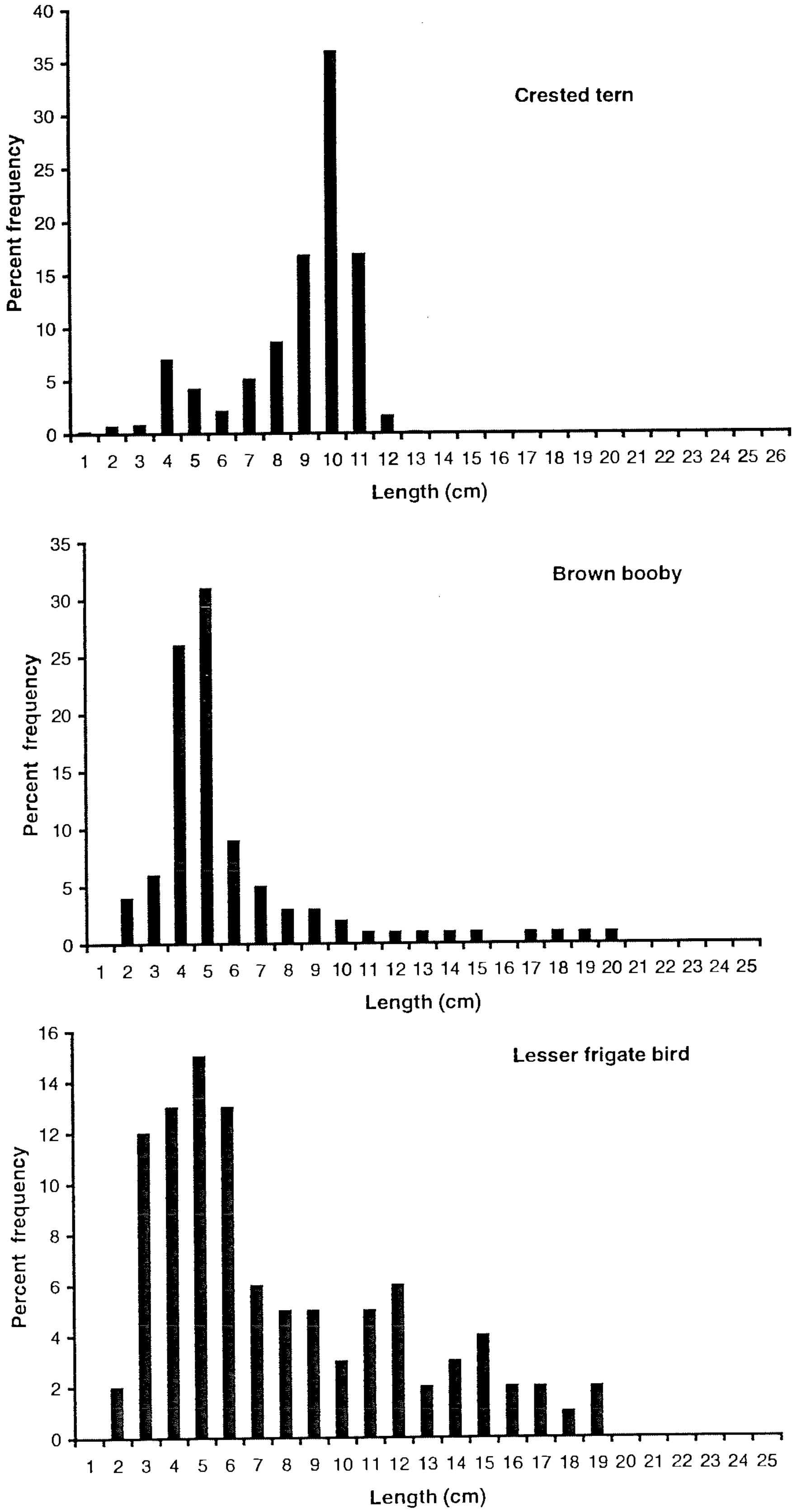


Figure 6.40 Length frequency distribution of fish eaten by Crested Terns, Brown Boobies and Lesser Frigatebirds in the northern Great Barrier Reef region. n = 1029 prey items for Crested Terns, n = 91 for Brown Boobies and n = 5283 for Frigatebirds.

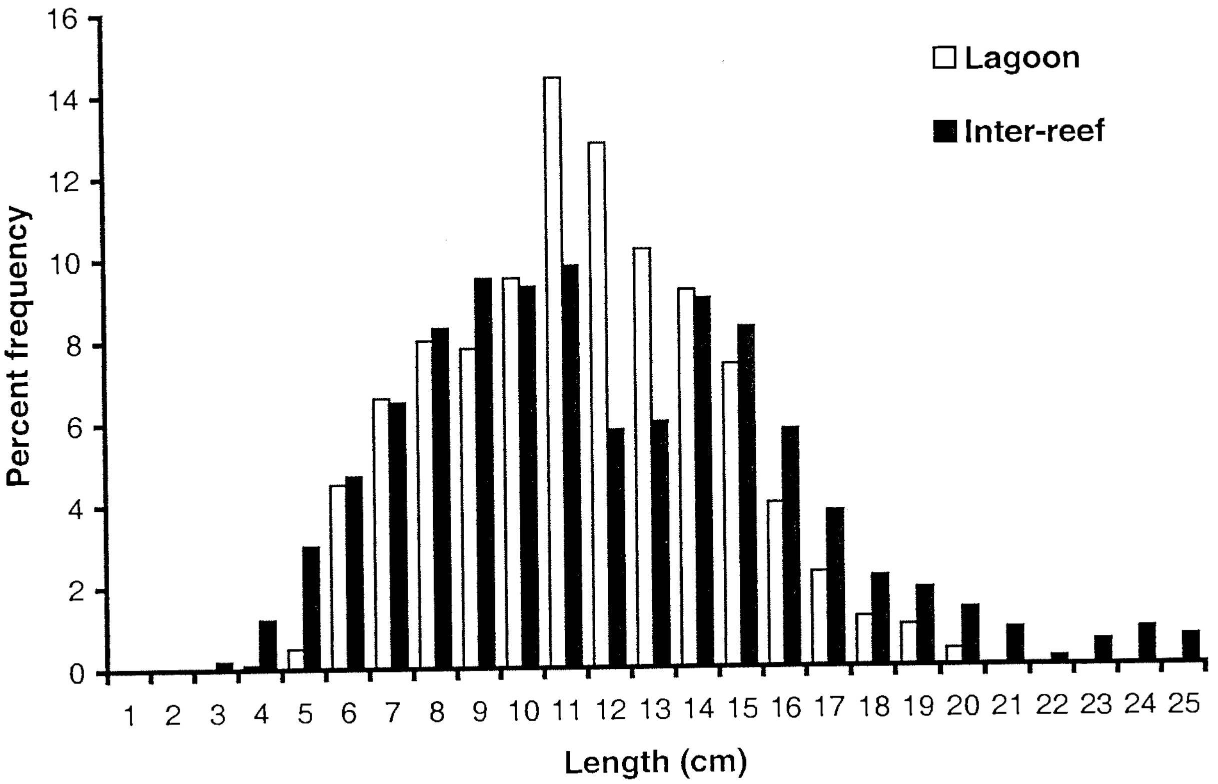


Figure 6.41 Size frequency of floating discard fish. Based on 3496 fish from inshore samples and 1435 fish from offshore samples.

APPENDIX.6.A

Table App.6.A.1 Sizes of fish caught by short and long tows (*n* = number of animals measured; ** indicates the mean length of this species was significantly different between short and long duration tows). Lengths in cm.

Species		Tows	Short trawl			Long trawl		
			n	Mean	SE	*n*	Mean	SE
Apistus carinatus	Inshore	20	103	9.6	0.0	133	9.6	0.1
*Apogon ellioti***	Inshore	20	114	8.1	0.4	143	9.3	0.2
Apogon fasciatus	Inshore	20	56	8.1	0.2	64	8.3	0.1
Callionymus grossi	Inshore	12	26	15.0	0.3	35	15.3	0.2
Canthigaster compressa	Onshore	13	42	5.4	0.0	19	5.5	0.1
Caranx bucculentus	Inshore	11	6	11.9	0.6	17	12.5	0.2
Choerodon cephalotes	Inshore	15	19	12.4	0.2	44	12.8	0.3
	Onshore	13	9	11.0	0.6	9	11.5	0.8
Choerodon suggilatum	Inshore	18	19	11.6	0.1	28	11.8	0.3
	Onshore	17	35	8.6	0.4	33	9.7	0.3
Dactyloptena papilio	Inshore	14	7	10.1	0.5	31	9.9	0.3
Engyprosopon	Inshore	18	60	9.2	0.0	103	9.1	0.0
Euristhmus nudiceps	Inshore	20	109	27.5	1.9	123	25.7	0.3
Fistularia petimba	Inshore	20	44	31.3	0.4	38	31.5	0.8
Lagocephalus sceleratus	Inshore	16	30	11.6	0.3	42	12.7	0.2
	Onshore	16	12	11.4	0.4	28	11.7	0.3
Leiognathus sp. **	Inshore	14	54	9.4	0.2	146	10.2	0.2
Lethrinus genivittatus	Inshore	20	307	12.2	0.1	384	12.5	0.1
	Onshore	20	251	11.2	0.1	305	11.2	0.0
Nemipterus furcosus	Inshore	20	420	15.3	0.1	635	15.5	0.1
	Onshore	19	82	12.0	0.3	140	12.4	0.4
Nemipterus hexodon	Inshore	16	30	15.1	0.3	61	15.5	0.4
Nemipterus peronii	Inshore	20	96	13.0	0.2	135	13.3	0.0
Paramonacanthus choirocephalus	Inshore	20	91	7.3	0.05	192	7.2	0.04
	Onshore	20	57	7.1	0.1	107	7.0	0.0
Paramonacanthus	Inshore	19	46	8.4	0.1	107	8.6	0.0
Pentapodus paradiseus	Onshore	20	7	13.5	0.1	5	13.5	0.1
Pentaprion longimanus	Inshore	11	6	8.2	0.1	13	8.5	0.1
Priacanthus tayenus	Inshore	20	101	14.7	0.1	247	14.9	0.1
Pristotis jerdoni	Onshore	17	178	7.1	0.0	62	7.1	0.1
Pseudomonacanthus	Inshore	13	5	15.4	0.1	24	13.8	0.3
Pseudorhombus	Inshore	19	22	17.2	0.9	30	15.4	0.5
Pseudorhombus spinosis	Inshore	12	11	16.0	0.7	9	15.0	0.8
Rhynchostracion nasus	Inshore	20	91	7.3	0.4	106	6.8	0.4
Saurida undosquamis	Inshore	19	87	18.8	0.6	114	19.7	0.4
Scolopsis taeniopterus	Inshore	20	259	13.0	0.2	292	13.7	0.2

Species		**Tows**	**Short trawl**			**Long trawl**		
			n	**Mean**	**SE**	*n*	**Mean**	**SE**
Siganus canaliculatus	Inshore	17	30	12.6	0.2	35	12.9	0.0
	Onshore	17	17	12.7	0.4	30	13.1	0.1
*Sorsogona tuberculata***	Inshore	20	38	11.0	0.3	52	11.5	0.1
	Onshore	11	10	9.6	0.2	16	9.7	0.3
Suggrundus isacanthus	Inshore	20	57	16.7	0.3	54	16.4	0.2
Synchiropus rameus	Inshore	17	22	10.8	0.1	38	11.0	0.1
Synodus hoshinonis	Onshore	17	39	10.9	0.2	52	10.6	0.1
Torquigener	Inshore	20	112	9.4	0.2	210	9.3	0.1
	Onshore	13	9	7.7	0.2	28	7.9	0.2
Upeneus asymmetricus	Inshore	12	27	12.5	0.5	22	12.7	0.2
Upeneus luzonius	Inshore	12	12	13.2	0.4	15	13.3	0.3
	Onshore	20	119	13.6	0.1	203	13.3	0.1
Upeneus sundaicus	Inshore	18	27	13.3	0.0	34	13.8	0.1
Upeneus tragula	Inshore	20	162	10.5	0.1	94	10.7	0.1
	Onshore	16	37	10.7	0.8	23	10.6	0.5

Table 6.A.2 Summary of seabird records collected from all sources from 9°00' S to 16°00'S. Listed by 30' latitudinal transects from the shore to the outer barrier, the time range sampled and the number of counts from this time range (*n* = number of counts).

Common name	Species	Latitudinal transect	Years sampled	*n*
Crested Tern	*Sterna bergii*	9°00'–9°30'	1979–1993	4
		9°30'–10°00'	1979–1979	2
		10°00'–10°30'	1978–1980	3
		10°30'–11°00'	1987–1995	14
		11°00'–11°30'	1980–1995	106
		11°30'–12°00'	1979–1995	107
		12°00'–12°30'	1977–1995	30
		12°30'–13°00'	1978–1995	17
		13°00'–13°30'	1978–1994	47
		13°30'–14°00'	1985–1995	43
		14°00'–14°30'	1978–1995	62
		14°30'–15°00'	1978–1996	109
		15°00'–15°30'	1978–1993	6
Lesser Crested Tern	*Sterna bengalensis*	9°00'–9°30'	1980–1980	1
		10°30'–11°00'	1989–1993	2
		11°00'–11°30'	1985–1995	20
		11°30'–12°00'	1987–1994	15
		12°00'–12°30'	1977–1994	7
		12°30'–13°00'	1978–1993	7
		13°00'–13°30'	1978–1994	22
		13°30'–14°00'	1986–1993	29
		14°00'–14°30'	1978–1993	26
		14°30'–15°00'	1981–1996	37
Bridled Tern	*Sterna anaethetus*	9°00'–9°30'	1979–1980	2
		10°00'–10°30'	1979–1980	2
		10°30'–11°00'	1987–1993	8
		11°00'–11°30'	1980–1993	29
		11°30'–12°00'	1979–1994	34
		12°00'–12°30'	1980–1995	14
		12°30'–13°00'	1980–1994	11
		13°00'–13°30'	1988–1992	9
		13°30'–14°00'	1987–1994	26
		14°00'–14°30'	1981–1994	17
		14°30'–15°00'	1982–1996	66
		15°30'–16°00'	1978–1978	1
Sooty Tern	*Sterna fuscata*	9°00'–9°30'	1993–1993	5
		10°00'–10°30'	1993–1993	1
		10°30'–11°00'	1989–1995	6
		11°00'–11°30'	1988–1995	8
		11°30'–12°00'	1988–1994	16
		12°00'–12°30'	1994–1994	1
		13°00'–13°30'	1986–1994	14
		13°30'–14°00'	1987–1993	12
		14°00'–14°30'	1984–1995	17
		14°30'–15°00'	1984–1994	8
Black–Naped Tern	*Sterna sumatrana*	9°00'–9°30'	1979–1980	2
		9°30'–10°00'	1979–1979	2
		10°00'–10°30'	1978–1979	2
		10°30'–11°00'	1987–1994	13
		11°00'–11°30'	1980–1995	46
		11°30'–12°00'	1980–1994	39
		12°00'–12°30'	1977–1994	13
		12°30'–13°00'	1981–1993	5
		13°00'–13°30'	1980–1994	29
		13°30'–14°00'	1987–1993	8

Common name	Species	Latitudinal transect	Years sampled	*n*
		14°00'–14°30'	1981–1994	15
		14°30'–15°00'	1978–1996	83
Roseate Tern	*Sterna dougallii*	9°00'–9°30'	1979–1979	1
		9°30'–10°00'	1979–1979	1
		10°00'–10°30'	1980–1980	1
		10°30'–11°00'	1992–1995	4
		11°00'–11°30'	1986–1995	19
		11°30'–12°00'	1986–1995	27
		12°00'–12°30'	1995–1995	1
		13°00'–13°30'	1986–1986	1
		13°30'–14°00'	1986–1992	8
		14°00'–14°30'	1988–1993	4
		14°30'–15°00'	1984–1994	7
Caspian Tern	*Sterna caspia*	10°30'–11°00'	1991–1995	3
		11°00'–11°30'	1988–1992	3
		11°30'–12°00'	1981–1995	10
		12°00'–12°30'	1986–1994	7
		12°30'–13°00'	1978–1991	5
		13°00'–13°30'	1978–1994	4
		13°30'–14°00'	1981–1995	17
		14°00'–14°30'	1977–1995	27
		14°30'–15°00'	1981–1996	38
		15°00'–15°30'	1978–1979	2
		15°30'–16°00'	1978–1979	3
Common Noddy	*Anous stolidus*	9°00'–9°30'	1979–1993	4
		9°30'–10°00'	1979–1979	1
		10°00'–10°30'	1980–1980	2
		10°30'–11°00'	1987–1993	5
		11°00'–11°30'	1980–1994	32
		11°30'–12°00'	1979–1994	28
		12°00'–12°30'	1980–1995	12
		12°30'–13°00'	1978–1994	6
		13°00'–13°30'	1980–1994	39
		13°30'–14°00'	1987–1995	14
		14°00'–14°30'	1980–1995	24
		14°30'–15°00'	1986–1996	21
Black Noddy	*Anous minutus*	10°30'–11°00'	1987–1993	7
		11°00'–11°30'	1976–1995	48
		11°30'–12°00'	1979–1995	41
		12°00'–12°30'	1980–1995	26
		12°30'–13°00'	1986–1994	11
		13°00'–13°30'	1980–1992	8
		13°30'–14°00'	1985–1995	19
		14°00'–14°30'	1981–1995	18
		14°30'–15°00'	1981–1996	43
Brown Booby	*Sula leucogaster*	9°00'–9°30'	1979–1993	4
		10°00'–10°30'	1993–1993	1
		10°30'–11°00'	1992–1992	1
		11°00'–11°30'	1980–1993	41
		11°30'–12°00'	1979–1995	51
		12°00'–12°30'	1980–1995	15
		12°30'–13°00'	1978–1992	8
		13°00'–13°30'	1978–1994	53
		13°30'–14°00'	1978–1993	20
		14°00'–14°30'	1978–1995	19
		14°30'–15°00'	1984–1996	21
Greater Frigatebird	*Fregata minor*	10°30'–11°00'	1992–1995	2
		11°00'–11°30'	1988–1995	15
		11°30'–12°00'	1987–1995	13

Common name	Species	Latitudinal transect	Years sampled	*n*
		12°00'–12°30'	1987–1995	9
		12°30'–13°00'	1991–1993	2
		13°00'–13°30'	1990–1990	1
		14°00'–14°30'	1981–1995	10
		14°30'–15°00'	1994–1994	1
Lesser Frigatebird	*Fregata ariel*	9°00'–9°30'	1979–1980	3
		10°00'–10°30'	1978–1979	2
		10°30'–11°00'	1993–1993	1
		11°00'–11°30'	1980–1995	38
		11°30'–12°00'	1979–1995	56
		12°00'–12°30'	1977–1995	16
		12°30'–13°00'	1977–1995	17
		13°00'–13°30'	1987–1991	5
		13°30'–14°00'	1992–1992	1
		14°00'–14°30'	1980–1995	17
		14°30'–15°00'	1981–1996	9
		15°30'–16°00'	1978–1980	2

CHAPTER 7

DISCUSSION

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CONTENTS

7 SYNTHESIS OF THE GBR EFFECTS OF TRAWLING STUDY AND THE IMPLICATIONS FOR MANAGEMENT

7.1 Major findings

There were several points of agreement at the 1989 Magnetic Island Effects of Fishing Workshop about the research that should be undertaken. Three of these were decisive in formulating the subsequent Effects of Trawling research project. The first was that the study should make use of the closed area (now known as the Green Zone) in the Far Northern Section of the Great Barrier Reef. The thinking was that it should be possible to identify the effects of trawling by comparing the condition in this large closed area, with that in the adjacent areas open to trawling. The second point was the belief that trawling had a massive impact. This was based on the information from the NorthWest Shelf, which suggested that a single trawl impacted or removed 90% of the epibenthos. Two additional but more subsidiary points were also raised. The first was the recommendation that an experimental approach should be used in the study. The second was that the fate and possible environmental impacts of trawler discards and especially possible impacts of discards on seabirds should be identified.

The study that was developed and approved by GBRMPA took these points into account in its design. Essentially, a comparison was to be made between the area that was closed to trawling (Green Zone) and adjacent areas that were open to trawling. In addition two manipulative experiments were to be carried out. The first was a BACI in which experimental trawling was to be used as an Impact on a series of experimental plots. The second was a Repeat Trawl experiment in which selected tracks were to be repeatedly trawled and the impact monitored. Finally a study of discards and the impact of discards on seabirds was planned as part of the overall study.

The Green Zone and the adjacent areas turned out to be complex morphologically with large stretches of unchartered water, shoals and reefs that made boat travel and especially trawling dangerous. Strong tidal currents between the shoals added to the difficulty of surveys. We established a Differential GPS system to provide accurate position fixing and following extensive echosounding (recorded at two second intervals while the research vessel was underway) collected a large amount of bathymetric information. This has been synthesised into a bathymetric chart as well as the three-dimensional views at the front of each volume.

The Green Zone could be divided into a series of strata. There were two broad zones, an inshore lagoon and the offshore zone. The latter is complicated consisting of an inter-shoal and inter-reef area which leads into an offshore lagoon bounded by the ribbon reefs on the edge of the continental shelf. Sediment analysis suggested that these zones could be divided into five strata on the base of particle size distribution (mud, sand and gravel) and carbonate content. Substrate is an important factor in deciding the distribution of marine benthic animals and so not surprisingly, the five stratum model turned out to be valid for the fauna of the area. Generally we found terrigenous sediments and high mud content in the inshore strata grading to a biogenically derived offshore sediment of sand and gravel with a high carbonate content.

A large biological survey was carried out of the study area. This was undoubtedly more comprehensive than any previous survey of the inter-reef section of the Great Barrier Reef. We used a video sled, a large dredge, a prawn trawl and a fish trawl to sample the entire area. Video transects showed that most of the seabed is relatively bare soft substrate with patches of epibenthic communities made up of a wide diversity of sessile invertebrates including sponges, hard and soft corals and gorgonians with a rich associated fauna of echinoderms, crustaceans and fish. The patchiness of the benthic communities can be visualised as islands of biodiversity in a sea of sand. There was high diversity in the study area: we sampled 763 invertebrate taxa in the dredge including 224 of molluscs, 166 of crustaceans, 121 of echinoderms, 88 of cnidarians, 84 of sponges, 54 of ascidians and 24 of bryozoans. We collected 504 species in the inshore strata and 608 in the offshore strata suggesting that both communities are rich in the number of species. There were 335 to 340 species common to both inshore and offshore sites. The epibenthic communities showed strong cross-shelf (east-west) variation. There was a decline in the number of species caught per trawl haul from 49 species per 15 min dredge sample inshore to 20 to 30 offshore but there was an increase in the biomass from 4 kg per haul inshore to 10 kg per haul offshore. Twenty-two species of prawns were found, six of these are commercially important to the prawn trawl fishery although only three, *P. esculentus*, *M. endeavouri* and *P. longistylus,* occurred in commercial quantities. Two broad groupings of prawn species were apparent: an inshore reef lagoon group, predominantly *P. esculentus* and *M. endeavouri*; an offshore shoal-reef group, predominantly *P. longistylus* and a suite of coral prawn species.

The fish fauna is also rich. We sampled a total of 340 species of fish in the Green Zone. Species area curves indicated that the sampling had probably captured the majority of species. The curves reached an asymptote more rapidly for inshore than for offshore species. This indicated more heterogeneity offshore than inshore. Most fish caught in fish and prawn trawls were small – over 85% were less than 30 cm in length. There was a change in the number and composition of species caught from inshore (166 to 180 species) to offshore (193 species). There was also a large overlap in the species composition with 111 to 119 species being captured in both areas. There was a change in total biomass of fish from around 132 kg per 30 min fish trawl inshore to around 55 kg per 30 min trawl offshore. A comparison of the catch from 122 paired fish and prawn trawls showed that although recreational or commercially important fish did occur in inter-shoal areas, extremely few were caught by the prawn trawl. With the single exception of *Diagramma pictum*, the prawn trawl did not catch juveniles of any recreationally or commercially important fish species.

The proposed comparison between the area closed to fishing with that open to fishing, depended heavily on the presumption that the closed area had not been fished since its closure in 1985. Logbook data had been collected but at a resolution of 30 min squares and these overlapped the Green Zone, thus fishing could not be accurately ascribed to inside or outside of the closed area. Private records of many skippers were analysed and combined with surveillance information. In addition during the course of the study, information at a 6 min resolution became available for part of the fleet. Trawl fishing recorded in logbooks showed that most effort in the area north and south of the Green Zone took place in the lagoon. The advent of GPS has enabled trawlers to fish the inter-shoal area to a greater extent than previously possible. It appeared that there has been a high level of illegal trawling in the Green zone and evidence that up to 40 to 50 boats regularly trawled the area. Misreporting of catch has taken place with catches from inside the Green Zone being credited to adjacent open areas. Illegal trawling in the Green Zone appeared to have taken place mainly in the lagoon, in and around the navigation channel and along the northern and southern boundaries. The offshore areas by contrast appeared to have had little or no effort largely because of the presence of uncharted reefs and shoals as well as the distance into the closed fishing area. We can safely conclude that enforcement of the trawling closure in the Green Zone has been ineffective and enforcement of this and other closures needs to be addressed by management agencies if the objectives of establishing the closures are to be met.

In order to compare the closed and open areas, we carried out a random sampling strategy to collect samples of the fauna at sites within the Green Zone and in the areas to the north and south. A total of 152 sites were sampled by fish trawl, 126 by prawn trawl and 157 by benthic dredge. Four data sets were analysed from these collections: prawns from the prawn trawl; bycatch (fish and invertebrates) based on prawn trawl catches; fish community based on fish trawl fish catches and benthic invertebrates from the dredge. The mean estimate of the power of the open versus closed comparison was the capability to detect a difference in fauna of at least 41%. We found no significant differences between the area closed to fishing (the Green Zone) and the adjacent open areas that could be attributed unambiguously to trawling. Many differences between the Green Zone and adjacent areas could have been due to environmental factors other than prawn trawling. The lack of an observed difference between the closed and adjacent open areas that could be attributed to prawn trawling was probably due to the existence and interaction of a number of the following features. We found that there was a very high level of natural variation in the population density of marine animals. We also found that the Green Zone was in fact partially trawled especially in the inshore strata. In addition a large part of the open area was not trawled. The GBRMPA 6 min grid analysis that became available during the study showed that the distribution of trawl effort in the open areas was highly variable both at the large scale (30 nautical mile grids) and the medium scale (6 nautical mile grids). Preliminary QFMA VMS monitoring data show that effort is also variable and not evenly spread over the available area at the small scale (1 nautical mile grids). In addition, we know that most areas are subject to very few trawls per year. The GBRMPA analysis showed that only seven of 200 grid squares (6 x 6 n.mile) were trawled sufficiently to have coverage amounting to more than twice a year. It was not possible to stratify our survey to take account of this variation in trawl intensity because information on trawl effort in the area was not available at a sufficiently high resolution at the time of the study and is still not available.

The significant differences in seabed communities that we found over the relatively small distance between the north and south open zones were probably related to differences in physical habitat. Nevertheless, the extent of these differences indicates there are likely to be significant large-scale latitudinal gradients in communities and biodiversity along the length of the whole Great Barrier Reef Marine Park. If GBRMPA wishes to capture representative examples of these communities and biodiversity in an undisturbed state, then it will be necessary to establish adequate appropriately zoned areas of each of the comprehensive range of continental-shelf habitats in the GBRMP.

We concluded from this part of the study that it will never be optimal to attempt to measure the impact of trawling solely by comparing areas open and closed to fishing, without additional supporting information. This is not simply because sampling a single ‘Green Zones’ is technically pseudo-replication. Even if there were several ‘Green Zones’, it is unlikely they would be true replicates or could be assumed to represent, in entirety, appropriate control sites within each ‘region’. This is due to a mismatch of scales of bio-variability and trawl effort, and because two conflicting requirements must be satisfied. These are firstly that the closed zones must be large enough to both encompass large-scale ecological processes and their component biological communities and also ensure compliance with no-trawl legislation (eg. edge effects). Secondly, they must be small enough (for Open vs Closed comparisons) so that there is no appreciable large-scale spatial trend in habitats. Also, it is unlikely that closed areas are ecologically identical to open areas prior to the start of trawling. We have shown that there exist significant habitat changes even at the medium scale (less than 15 n.mile). There are additional reasons why solely comparing areas open and closed to trawling, even with several 'Green Zones', is not an optimal method for assessing the impact of trawling. These include the uneven patchy spatial distribution of trawl effort in open areas, at all scales from metres to hundreds of kilometres, as well as significant open areas that are untrawled. Further, the overall average level of trawling effort is low, in relation to the level estimated to cause statistically detectable impact. It is also low compared with heavily fished areas on other parts of the coast such as Moreton Bay or in other parts of the world such as in the North Sea or the Gulf of Thailand.

We have concluded that even fully replicated two-state comparisons (open vs closed) are not an optimal method. We suggest the most appropriate way to estimate what the effects of trawling have been in the bulk of the GBR lagoon will be to precisely identify and sample, in several regions of the GBR, many replicate small-scale sites on a gradient of the full-range of actual trawl intensities. Green Zones may provide a source of untrawled control sites. It will never be possible to completely remove the problem that the original (pre-fishery) condition of the trawled sites may have been different from the condition of the unfished control sites. Nevertheless, this problem should be minimised by ensuring that chosen sites be as similar as possible in terms of physical habitat and environmental position. Further, there should be at least as many controls as trawled sites and these should be intermingled as much as is possible. This suggested multi-state approach would have more interpretive power. Any real trawl effects should show a trend with trawl intensity, and will be less sensitive to spurious confounding effects. Before this, a controlled depletion-experiment on soft-sediments should be conducted to provide pilot information that is necessary for designing the larger-scale sampling. This would also enable estimation to be mad of the impact rates for soft-sediment fauna. A depletion-experiment would also complement the larger-scale sampling and provide corroborative evidence on the effects of trawling on soft-sediment fauna. This approach will require grid-scale and fine-scale information on trawl effort distribution, and ecological information on the distribution of habitat types. The introduction of VMS to the trawl fleet will greatly assist in understanding and quantifying the pattern and extent of trawl effort. The usefulness of the data will depend on the number of times a night the position of each vessel is checked (polling rate). A high polling rate will be necessary at least in some areas to accumulate information on the intensity of trawling over discrete parts of the seabed. The ecological information may become available in the near future, from a range of proposed projects. Consequently, it should soon be possible to conduct such an experiment.

A BACI (Before-After-Control-Impact) experiment was set up in the Green Zone in areas that were suitable for trawling but were apparently untrawled. Twenty-four plots 2.7 x 1.2 km were identified and twelve of these were trawled all over once (Impact) and the remainder were used as controls. All plots were then resurveyed to give Control and Impact information. Despite the removal of around 40 t of benthos and contrary to the prior expectations of GBRMPA, the scientists involved in the design of the project, prior evidence and community perceptions; the BACI single-coverage experiment produced no detectable impact. The BACI experiment was expected to have an 80% statistical power to detect a reduction of 70-90% in biomass, and for most taxonomic classes the experiment was more powerful than the *a priori* estimate. We conclude that the impact of a single trawl coverage in the FNS of the GBR must be smaller than 90%. The apparent density of benthic invertebrates sampled by prawn trawls was much smaller than by the benthic dredge suggesting an average removal rate much closer to 0-10% than 90-100% per trawl. The second manipulation experiment was the Repeat Trawl depletion experiment in which 13 trawl tows were made along the same track in each of 6 plots. Records were kept of the catch from each tow and in addition non-destructive video sampling was made to record changes during the course of the depletion. The results of this experiment also suggested that each trawl removed 10-15% of that part of the sessile benthos community, the mobile benthos community and the fish community that are vulnerable to trawling.

We can conclude from these two manipulative experiments that the impact of a single prawn trawl is considerably less than had been previously thought. In addition we established that the composition and quantities of benthos caught in prawn trawls does not give a representative picture of the benthic invertebrate community because the gear is selective. A prawn trawl is relatively good at catching crustaceans (40% efficiency relative to dredge) and relatively poor (0-10% efficiency relative to dredge) at catching most other benthic organisms – whether sessile or mobile. Consequently data from prawn trawl catches in the repeat-trawl experiment do not show which organisms are completely unaffected by trawling, or which organisms are fatally damaged but not removed. We know that prawn trawlers do not follow a 'wheat field harvesting' spatial distribution in which the whole trawl ground is trawled at the same intensity. VMS data from vessels operating in the prawn fishery shows that prawn trawlers tend to 'work' an area for a number of days, to trawl many times along paths they have previously found productive, and to avoid those they found unproductive or hazardous. The result is that the trawl impact is extremely variable, with most areas receiving little or no impact while others are trawled repeatedly.

Our monitoring did not include infauna, mainly because experimental work has shown otter trawls (< biblio >) do not impact that infauna. Infauna can be severely impacted by heavy beam trawls used for catching benthic fish. Bergman and Hup (1992) for example found depletion rates of 10 to 65% of benthic infauna following only three passes of a heavy beam trawl. Scallop dredges also impact on infauna. Eleftheriou and Robertson (1992) carried out experimental dredging and found that it caused destruction of large epifaunal organisms but also destroyed many large infaunal organisms including molluscs, echinoderms, crustaceans and burrowing sand eels.

The apparently lower level impact of a prawn trawl in the northern GBR compared to the North West Shelf is probably due to the latter study having been targeted at that portion of the seabed benthos that is most vulnerable to trawling – namely large sponges. The GBR study by contrast considered all sponges including the many small species that are unlikely to be impacted and it also considered the full suite of epibenthic species. Repeat-trawl-style experiments in the GBR inter-shoal areas can provide very useful information on trawl depletion rates. The results of each experiment are applicable only to a small subset of the marine community because of the variability of the seabed ecosystem and so they would need to be duplicated in a range of appropriate habitats. The data set from the repeat-trawl experiment is a prototype for the type of information that could be collected once VMS is operational. However even VMS data will not provide the fine level position information used in the repeat trawl experiment. Repeat-trawl data provides a good basis for developing a more complex mathematical/statistical model that addresses some of the issues that have been identified in this experiment but have not yet been built into a model. The current project was not able to give any estimate of recovery rates. However it is essential to measure the rate at which the community recovers in order to determine the real impact of trawling which is an interaction between the dynamics of depletion and recovery.

Bycatch samples were collected from 79 research prawn trawls in the inshore region and 43 in the inter-shoal region both within the Green Zone and the areas to the north and south of the closure. The mean catch rate of bycatch by a single prawn trawl net was 37 kg per hr in the lagoon and 55 kg per hr offshore. Most of the difference was due to the offshore catch rate of invertebrates being about double that of the inshore catch rate. Fish and crustaceans dominated the bycatch. Fish made up around 72% of discards by weight from lagoon trawls but only 60% of inter-shoal discards. Crustaceans accounted for 7% of the bycatch weight from the lagoon and 13% from the inter-shoal area. Most of the bycatch taken in prawn trawling in the Far Northern Section of the Marine Park has little or no commercial value and will be discarded. Introduction of BRDs using designs currently available would lead to a reduction of about 20% in the amount of bycatch taken by prawn trawlers. This would reduce the impact of trawling on small demersal animals and especially on fish that have a particularly low survival rate from trawling.

Previous research has shown that over 90% of fish are dead when discarded from prawn trawls. In the case of crustaceans, robust forms such as crabs tend to have a high survival when discarded whereas more delicate forms including non-commercial prawns are nearly all dead. We estimated that about 80% of the discards are dead when dumped. Between 34 and 40% of discards by number and weight from the lagoon floated compared to only around 10% of discards from the inter-shoal area. Fish made up nearly all of the floating discards. Thus a large proportion of the discards is available to be taken by surface scavengers. We saw little scavenging of floating discards at night but during the day seabirds (mainly Crested Terns and Frigatebirds), dolphins and sharks were seen to take discards at the surface. Because seabirds only take floating fish that are mostly less than 12 cm in length and because most fish sink, it was estimated that seabirds account for only a minor part of the discards. Most discards sink to the seabed, our observations showed that teleost fish and sharks were the most important scavengers of discards on the seabed. Scavenging on the seabed was rapid, most baits were eaten within 30 min. Discards are dumped while the trawler is underway and consequently they are widely dispersed. This spreads their availability and makes impacts unlikely except on species that can forage over large distances. In the study area the only group capable of this extensive foraging was the seabirds.

We analysed diet samples from 12 species of seabird in the far northern section of the GBR. Trawl discards were important in the diets of only three species (Crested Tern, Brown Booby and Lesser Frigatebird). They were of minor importance to another four species and were not eaten by another seven species that were investigated. No seabird species was entirely dependent on discards, but the diet of Crested Terns consisted largely of discards during the trawling season. No effects of discards were detected on any seabird populations with the exception of those of the Crested Tern. Populations of this species have increased by two orders of magnitude in the far northern Great Barrier Reef since trawling began.

7.2 Extension of the results to trawled areas of the GBR region

7.2.1 Introduction

The results from our experiments provided information to assess the impacts of intensive trawling and extensive trawling. In the BACI experiment, the entire area of treatment plots was trawled once, and though an impact was quantified, it was not possible to detect this impact on the seabed. This suggests that sparse or occasional trawling does not have an obvious or easily measurable effect. In the depletion experiment, the area of treatment tracks was trawled repeatedly 13 times, and the cumulative impact was quantified and readily detected on the seabed. This suggests that concentrated, repeated trawling has a substantial effect. Further, the rate of removal (resilience) was dependent on the type of organism; some types were more easily removed than others.

Clearly, understanding the overall effects of trawling is dependent on the distribution and intensity of effort. This is known to be patchy. In this section, we have estimated the depletion rate of attached fauna subject to a range of trawl intensities observed in the fishery; the total annual removal of fauna from the GBRMP; and the possible status of populations of attached fauna after 20 years of trawling. In attempting to estimate population status, we have used a simple model for possible recovery dynamics of fauna.

This extension of the results to trawled areas of the GBR Marine Park is speculative, and several assumptions were necessary in order to proceed with the analysis. These assumptions relate to: the distribution of effort among grids; the fine scale distribution of effort within grids; the effects of trawling on soft-sediment fauna; the distribution of fauna and the recovery rates of fauna. Though greater rigour will require good information on these assumptions, this analysis will provide a preliminary estimate for the overall effects of trawling and will indicate directions to follow. The approach taken here would be applicable to other issues affecting trawl industry and its management; such as impacts on bycatch populations and for scenario modelling of the consequences of a range of different management interventions.

7.2.2 Resilience of different attached fauna

The depletion experiment showed removal rates that varied between about 5% to 20% for different species. A follow-on project to measure the recovery of the depletion tracks has provided data on how the on-ground density of several species decreased with trawl intensity. Examples of these results are summarised in Fig 7.2.1 for four species. The trajectories begin with the observed average un-trawled densities in patches of epibenthic habitat and show population decline when the average depletion rate was applied. Sea-whips (Junciella sp.) were the most resilient, their density decreased at a rate of ~5% per trawl; one sea-fan species (Ctenocella sp.) decreased at ~14% per trawl, a fan-sponge (Ianthella sp.) decreased at ~20% per trawl, and least resilient were flower pot corals (Turbinaria sp.) which decreased at ~40% per trawl. Note that even the most resilient types suffered increasing damage with trawling; eg. about 10–30% of gorgonians were dead after 13 trawls. It is clear from this example that the amount of depletion of any given species depends the number of times a given area of seabed is trawled, at the spatial scale of metres. In the discussion below, we have considered types of fauna with high, medium and low resilience that are removed at rates of 5%, 10% and 20% per trawl, respectively.

7.2.3 Distribution of trawl effort among 6 minute grids

Clearly, to extend the results of this study and understand the possible overall impact of trawling on the GBR inter-reefal seabed we need to have information on the distribution of trawl effort at large and small scales. Recently, information has become available from GBRMPA on large scale patterns of trawl effort at 6 min grid resolution (ie. trawling recorded in grids of size 6 minutes of latitude by 6 minutes of longitude; approx. 10 × 10 km). This has been achieved by re-interpreting logbook data collected for 30 min grids at the smaller scale based on the distribution of effort recorded in more detailed research logbooks completed by ~30% of the fleet (Fig 7.2.2, Francis Pantus, GBRMPA). It appears from Fig 7.2.2 that trawling has been very extensive in the GBR Marine Park, with effort recorded in about 1300 6 min grids in 1996, an area equivalent to about 153,000 km^2. About 57,500 km^2 (~27%) of the non-reef shelf area had no effort recorded at this scale. It is also clear that effort is highly aggregated (Fig.s 7.2.2, 7.2.3). The cumulative distribution of grid area (Fig.7.2.3) shows that 70% of grids were trawled relatively lightly, with <1,000 hrs of effort, and only 5% of grids were trawled relatively heavily, with >3,000 hrs of effort. The degree of aggregation of effort is shown by the cumulative distribution of grid effort vs area (Fig.7.2.3). The most intensive 20% of the effort was concentrated into <5% of trawled grounds — at the other extreme, the most extensive 20% of the effort is spread over about 60% of the trawled grids. The remaining 60% of effort is aggregated into about 40% of the trawled grids (medium).

7.2.4 Distribution of trawl effort within 6' x 6' grids

Information on the spatial intensity of trawling within grids at fine scales is very limited. Some data collated from GPS plotters in the NPF (CSIRO unpubl.) and trials of VMS in the Queensland Trawl Fishery (QFMA) show that trawling is highly aggregated at fine scales as well as at the 6 min grid scale. To place the results of this report in the context of the possible spatial distribution of trawl effort within grids, as well as among grids, we have assumed that the level of aggregation within a grid divided into 30 × 30 m pixels was the same as among 6 min grids. That is, the actual distribution of effort among 6 min grids (see Fig 7.2.3: cumulative %grid-area vs effort) was used as an empirical distribution function to distribute different amounts of effort among 30 m pixels within grids. The examples of different levels of effort that we have illustrated (Fig.7.2.4) represent a range observed in the Queensland Trawl Fishery, ie. 500, 1000, 2000, and 4000 hrs per grid. For vessels towing 5 fathom quad-gear at 3 km for 11 h per night, these effort levels are approximately equivalent to, respectively, about 40, 80, 160 and 320 vessel days per 6 min grid. If the trawl paths had been laid out uniformly on the seabed, ~1,000 hrs would be sufficient to trawl an entire grid. Thus, these effort levels correspond to 50%, 100%, 200% and 400% coverage of a grid.

The fine scale distributions of the intensity of aggregated trawling among 30 m pixels (Fig. 7.2.4) showed that as the level of effort increased, relatively more pixels were not trawled than for random trawling (or for uniform trawling) and some pixels were trawled much more often than the average level of coverage. For example, at 4,000 hrs of effort (400% coverage), random trawling leaves ~0% of the pixels untrawled whereas aggregated trawling might leave ~20% of the pixels in a grid untrawled. On the other hand, with aggregated trawling a very small percentage of the pixels were trawled more intensively than with random trawling. For example, with 4,000 hrs of random trawling, the highest intensity was 15 times, whereas with aggregated trawling the highest intensity was about 30 times (Fig. 7.2.4d).

Combining the information on the fine scale distribution of effort and our experimental results gives an indication of the areas of seabed within grids that could be expected to be trawled each year as intensively as our BACI (1×) and Depletion (13×) experiments. From Fig.7.2.3, about 60% of grids were trawled with less than ~750 hrs (coverage <75%) and in the case of grids with 50% coverage, about 40% of their area may be trawled with an intensity ≥1× but none trawled ≥13× (Fig.7.2.4a). Fewer grids (~25%) are trawled with between 750–1500 hrs (Fig.7.2.3) effort (75%–150% coverage) and in the case of grids with 100% coverage, about 60% of their area may be trawled with an intensity ≥1× but none trawled ≥13× (Fig.7.2.4b). Only about 12% of grids are trawled with 1500–3000 hrs effort (150%–300% coverage) and in the case of grids with 200% coverage, about 70% of their area may be trawled with an intensity ≥1× and about 1% trawled ≥13× (Fig.7.2.4c). Few grids (~5%) are trawled with >3000 hrs effort (≥300% coverage) and in the case of grids with 400% coverage, about 80% of their area may be trawled with an intensity ≥1× and about 5% trawled ≥13× every year (Fig.7.2.4d).

7.2.5 Estimation of faunal biomass removed by trawling in the GBR

The experimental results (benthos removal rate per trawl, eg. Fig. 7.2.1) and effort distribution (within and among grids, eg. Fig.s 7.2.4 and 7.2.3) can be combined to estimate the amount of benthos removed by trawlers from trawled grids in inter-reefal areas. This estimation assumes that trawling is not biased toward or away from benthos patches on the seabed, and takes into account only one 'simulated' year of trawling. If the depletion rate was, for example, 10% of benthos biomass per trawl, then 50% effort coverage might remove about 5% of the benthos from the seabed (Table 7.01), whereas 400% effort coverage might remove about 29%. Where trawling is intense (eg. 400% coverage) and the removal rate is high (eg. 20%), the difference between the amount removed by aggregated trawling and simpler distributions of effort (ie. random or uniform) is large (Table 7.01). Where trawling is light (eg. 50%coverage) and/or removal rate is low (eg. 5%), within grid effort distribution has little effect on the amounts removed. The assumption about bias in benthos distribution is important as some information from the Gulf of Carpentaria indicates that areas adjacent to structured habitats are being targeted for prawns, and anecdotal reports from the development phase of the inter-reefal redspot king prawn fishery off Townsville suggested that vessels typically removed about 200 t of sponges each per year for the first 3 years (Brett Shorthouse, pers. comm.). Targeting of such areas by significant numbers of vessels is likely to have a detrimental effect on biodiversity in the GBR World Heritage Area.

Table 7.01 Total percentage of benthos removed from a grid for a range of removal rates (5%, 10% and 20%) and prawn trawl effort coverages (50%, 100%, 200% and 400%) for uniform, random and aggregated distribution of trawl effort.

	Benthos removal rate from a 6 min grid, per year								
	5%	5%	5%	10%	10%	10%	20%	20%	20%
Effort Coverage	Unif.	Rand.	Aggreg.	Unif.	Rand.	Aggreg.	Unif.	Rand.	Aggreg.
0	0	0	0	0	0	0	0	0	0
50	2.5	2.5	2.5	5.1	4.9	4.9	10.6	9.5	9.4
100	5.0	4.9	4.8	10.0	9.5	9.2	20.0	18.1	17.2
200	9.8	9.5	9.1	19.0	18.1	16.8	36.0	33.0	29.2
400	18.5	18.0	16.7	34.4	32.8	28.9	59.0	54.9	45.5

Table 7.02 Distribution of 1996 trawl effort among trawled 6 min grids for the GBR region. Effort is shown as a coverage; i.e., the percentage of the grid that would be trawled if distributed uniformly. The number of grids in each coverage is shown in classes of 25%.

Effort coverage	# grids	% Area	Cumulative % area
>0.01	241	19.6%	100.0%
0.25	235	19.1%	80.4%
0.50	232	18.9%	61.2%
0.75	154	12.5%	42.3%
1.00	102	8.3%	29.8%
1.25	62	5.0%	21.5%
1.50	49	4.0%	16.4%
1.75	29	2.4%	12.5%
2.00	33	2.7%	10.1%
2.25	12	1.0%	7.4%
2.50	15	1.2%	6.4%
2.75	8	0.7%	5.2%
3.00	10	0.8%	4.6%
3.25	6	0.5%	3.7%
3.50	8	0.7%	3.3%
3.75	7	0.6%	2.6%
4.00	3	0.2%	2.0%
4.50	3	0.2%	1.8%
4.75	3	0.2%	1.5%
5.00	2	0.2%	1.3%
5.25	5	0.4%	1.1%
5.50	2	0.2%	0.7%
5.75	1	0.1%	0.6%
6.75	2	0.2%	0.5%
7.00	1	0.1%	0.3%
7.75	1	0.1%	0.2%
8.00	1	0.1%	0.2%
8.25	1	0.1%	0.1%

This estimate can be extended further, for all trawled 6 min grids in the GBR region 10°40'S to 24°30'S, based on available 1996 trawl effort data. By applying the estimated annual removal rates for grids (see Table 7.01 for examples) to the actual 1996 effort in each grid for the whole GBR region (Table 7.02), we estimated how much benthos was removed from the GBR region in 1996. Given the aggregated trawling scenario, if the benthos removal rate was 5%, the percentage of benthos removed in 1996 from the 1300 trawled grids may have been ~4.4%; if the rate was 10%, then ~8.3% was removed; if 20%, then ~15.4% was removed (Table 7.03(a)). If the whole area of continental shelf in the GBRMP is considered (ie. ~1790 grids), then the percentages of benthos removed may have been 3.2%, 6.1% and 11.2% respectively for rates of removal of 5%, 10% and 20% per trawl.

Table 7.03 Estimation of the percentage of benthos removed from 1300 trawled 6 min grids for benthos with different rates of removal (resilience), based on 1996 trawl effort. (a) annual overall rate of benthos removal; (b) depletion after 20 years trawling with no recovery; (c) 20 yr depletion with a range of recovery rates (expressed as the fraction (max.) of the population replaced in 1 year).

(a) Annual depletion of trawled grids

	Benthos removal rate per trawl			
	5%	10%	20%	Mean
Overall removal	4.4	8.3	15.4	9.3

(b) Benthos removed after 20 years, with no recovery

	Benthos removal rate per trawl			
	5%	10%	20%	Mean
Overall removal	59.4	82.2	96.5	79.3

(c) Benthos population level depletion after 20 years, with recovery

	Benthos removal rate per trawl			
Recovery Rate	5%	10%	20%	Mean
1/2	2.8	8.3	15.4	8.8
1/5	5.5	10.3	19.2	11.7
1/10	11.0	20.3	35.5	22.3
1/20	20.6	35.3	54.8	36.9
Mean	10.0	18.6	31.2	19.9

The whole-of-GBR analysis is relatively insensitive to the assumption about the distribution of effort within grids (cf. uniform, random, aggregated), compared with input factors such as removal rates or total effort. The reason is that relatively few grids are trawled very intensively. Nevertheless, we persisted with the aggregated model because it does resemble trawling behaviour more closely. The aggregated model also indicates that slightly more than half of the overall area within the 1300 grids with recorded effort may not be trawled in any given year.

These estimates of the amount of benthos removed (Table 7.03(a)) are for only 1 year, but most grids in the GBR have been trawled repeatedly each year for more than 20 year. If these removal rates were compounding over the past 20 years, with a pattern of effort like 1996, then types of fauna with low resilience (ie. 20% removal rate) would be almost completely from trawl grounds (Table 7.03(b)) — note that flower pot corals (Turbinaria sp.) are even less resilient (removal rate ~40%, Fig. 7.2.1). Even the most resilient faunal type would be severely depleted (by ~60%, Table 7.03(b)). However, it is unlikely that these faunal populations would not have some ability to recovery to some extent and so we need to consider recovery dynamics.

7.2.6 A simple model for recovery dynamics

At present there is virtually no quantitative information on the recovery dynamics of benthic fauna — it is generally accepted that most sessile fauna will take many years or decades to recover. However, it is likely that recovery times will be a continuum and some benthos may recover quickly. It is common knowledge that species such as prawns can replace their populations in 1–2 years. Indirect evidence from the work of Sainsbury et al (1997) on Australia's North West Shelf suggests that large sponges may take more than 15 years to recover. In this section we have endeavoured to cover a range of possible recovery dynamics based on a simple logistic population growth model:

(1) $$B_{t+1} = B_t + rB_t\left(1 - \frac{B_t}{K}\right)$$ Lotka (1925), Voltera (1926)

where Bt = biomass at time t, r = growth coefficient, and K = carrying capacity. Although there has been endless debate about the applicability or otherwise of this form of population growth model, in the absence of any empirical data on recovery dynamics, it will serve the illustrative purpose of this discussion. With t representing years in this case, r was set to take values 0.2, 0.4, 0.8, 2.0 corresponding to slow through fast recovery. With this model, the maximum rate of population growth occurs when the population is at half (50%) of carrying capacity (100%). The maximum annual growth rates corresponding to the values of r were 5%, 10%, 20%, 50%. In terms of length of recovery times from a 50% impact, these rates corresponded to about 20 yrs, 10 yrs, 5 yrs, and 2 yrs respectively to return to K (~100%; see Fig. 7.2.5b). Of course, recovery times depend on the extent of impact. If for example there was a one-off impact of 10%, recovery of the population of a given type of fauna would be much faster than for a one-off impact of 90% (see Fig. 7.2.5).

These four different recovery rates were combined with the three different removal rates (5%, 10%, & 20% = resilience) discussed above, to provide 12 different types of hypothetical fauna that would represent a somewhat realistic spectrum of faunal vulnerability, from low resilience & low recovery, through medium resilience & medium recovery, to high resilience & high recovery. The removal rate was included as an another term in the population growth model:

(2) $$B_{t+1} = B_t + rB_t\left(1 - \frac{B_t}{K}\right) - dB_t$$

where d = the proportional benthos removal rate for the given amount of effort applied.

In this hypothetical scenario, the addition of a capacity for recovery appears to substantially alter the status of benthos populations after 20 years of trawling, compared with that presented in Table 7.2.3b. This is illustrated by the 20-year time trajectories for populations of three faunal vulnerability types in a grid trawled with an average level of effort (Fig. 7.2.6). If there was no population growth, all three faunal types would eventually disappear from grids, but with population growth, all three faunal types will probably sustain some level of abundance at different points below their original "carrying capacity"; at least at average levels of effort.

However, in grids with higher levels of effort, some vulnerable faunal types will almost certainly disappear (see below).

7.2.7 Estimation of status of faunal populations after 20 years trawling in the GBR

We have shown that different fauna have different resilience to removal by trawl gear and that, because trawling is aggregated, there is not a direct relationship between the amount of effort and the amount of seabed fauna removed. Aggregated trawling may provide 'refuges' that, by accident or intent, are trawled only rarely or not at all. The higher the level of aggregation, the greater extent of untrawled areas. However, we do not know how dynamic the pattern of effort aggregation is, or whether the accidental 'refuges' persist from year to year. We have also shown that if fauna have no capacity for recovery, then with repeated trawling, all trawled seabeds will eventually become completely denuded of fauna. With capacity for recovery, then all faunal vulnerability types have the potential for reaching a population level that is balanced by the amount removed by trawling — this balance is highly dependent on faunal vulnerability and the intensity of trawling.

The status of the 12 faunal vulnerability types, in grids trawled with different levels of effort, after 20 years from the start of trawling is illustrated in Fig. 7.2.7. In grids with higher intensities of effort, the population size of the faunal types, as a percentage of the starting size, was progressively less. The population reduction was much more severe for the more vulnerable faunal types. The most vulnerable faunal type was removed in the ~5% of grids trawled with >3,000 hrs of effort each year. Two more faunal types were removed in grids trawled with 4,000–6,000 hrs of effort, and another three were driven down to very low numbers in grids with >7,000 hrs of trawling. At the other extreme, the least vulnerable faunal type was reduced by only ~17% in the most intensively trawled grids. Because of these differences among faunal types, the composition of seabed communities could be greatly altered by trawling — even for grids with average trawl intensity (~700 hrs yr •^{1}). As the intensity of effort increased in grids, so did the degree to which the composition of seabed communities was altered — more than 50% of grids were likely to have substantially altered community composition. Thus trawling reduces the proportion of vulnerable species and trawled grids become progressively dominated by the least vulnerable fauna.

The overall status of the 12 hypothetical faunal vulnerability types, across all trawled grids in the GBRMP, after 20 years from the start of trawling, was estimated by summing the status for each over grids trawled with different levels of effort. Over all 1300 trawled grids, the population level of the least vulnerable faunal type was down ~3% from an untrawled state compared with the most vulnerable faunal type, which was down ~55% from an untrawled state (Table 7.2.3c). If we assume that all 12 faunal types started with the same biomass, then the overall mean faunal population level was down ~20%, albeit with substantially altered community composition.

7.2.8 Extension of the results

This extension analysis suggests that though 50-70% of trawled grids have been trawled only lightly (<700–1000 hrs) each year, over the last 20 years the cumulative effect of this in trawled grids has been that (1) vulnerable types of fauna (ie. those easily removed and/or slow to recover) have been severely depleted, thus causing (2) substantial changes in the composition of the faunal community, and (3) the overall faunal biomass may have been reduced by ~20%, but it would be dominated by less vulnerable species.

Caution is needed in accepting these conclusions because the analysis is a highly simplified abstraction of the real situation and we have made several assumptions. These assumptions include: (1) the range of resilience and recovery parameters used, whereas some real fauna may be even more vulnerable while others may be less so (also, only removal rates were considered, other damage known to occur and potentially causing mortality was not included); (2) that the distribution of faunal types was unbiased relative to trawling, whereas real trawling may avoid or target structured habitat; (3) that the pattern of effort for 1996 was representative and unchanging for the past 20 years; (4) that aggregated effort within grids could be represented by the empirical distribution of effort among grids; (5) that the resilience and recovery rates used would also be representative of soft-sediment fauna; and (6) that the starting biomass of fauna was evenly distributed across the 12 different vulnerability types, whereas in reality this is unlikely. Further, source-sink issues related to recruitment have not been considered. The consequences of these assumptions are that the real situation could be better or worse than the conclusions presented above. In addition, this analysis was conducted only for 1300 grids with recorded effort, which totalled ~153,000 km²; another ~57,500 km² (~27%) of inter-reefal grids had no effort recorded in 1996.

This analysis suggests that the impacts of trawling have the potential to be ecologically sustainable, if there is appropriate management of these impacts. The type of modelling presented in this section can assist by indicating the potential consequences of a range of management scenarios, though some additional important information will be required for more rigorous modelling. The kinds of information required include: (1) the distribution of effort among 6 min grids (this is becoming available with the research logbooks); (2) data on the recovery rates of different fauna (this is an objective of a follow-on project); (3) the fine scale distribution of effort within grids (this will become available with the implementation of the VMS); (4) data on trawl effects on soft-sediment fauna (proposal under development); and (4) the distribution of seabed habitats and fauna throughout the GBR region (collaborative proposal submitted to NHT).

The results from this extension analysis can also provide some insight for the interpretation of the Open vs Closed Comparison. The Open vs Closed Comparison was sufficiently powerful to detect a reduction in population to ~40% of un-impacted levels. In the extension analysis (Fig. 7.2.7) for the most vulnerable faunal type, more than 1,000 hrs of effort per year for 20 years was required to depress the population below ~40%. However, only 6 of the 31 sampled open zone grids were trawled with more than 1,000 hrs of effort in 1996 and therefore might have been expected to have had detectable effects. Our ability to detect any effects in these 6 grids would have been diluted by the data from the other 25 Open grids subject to less trawl effort (12 of which may not have ever been trawled). Further, the integrity of the closed zone as a measure of un-impacted levels was compromised. At least 14 of 50 closed grids were trawled in 1996 and 11 of these were trawled with about average levels of effort (500-750 hrs), which may have been sufficient to depress the most vulnerable faunal population down to ~60%. This in effect lowered the detectable effect size down to about 25% — the effort required to depress the population below 25% was ~1200 hrs (Fig. 7.2.7) and only 3 open zone grids were trawled with more than ~1,200 hrs of effort in 1996.

The results from this extension analysis can also guide design of any future research to answer questions about past effects in previously trawled grounds on soft sediments of the main lagoon. Clearly, as higher quality effort distribution data becomes available, grids to be sampled could be carefully selected, with replication, across a range of exposures to trawl effort. A range of effort levels should be sampled eg. 0, 500, 1000, 2000, 4000, & 8000 hrs per year and sampling within grids should take account of aggregated trawling intensity. Closed Zones could be scrutinised for the possible existence of true controls (ie. 0 effort). Of course, all sampled grids would have to be as similar as possible in all respects except trawling. Intensive repeated experimental trawling on soft sediments in a truly closed zone would be a useful pre-requisite to further guide the design of larger scale sampling of grids by providing removal/impact rates for soft sediment fauna's.

7.3 Management of the Great Barrier Reef Marine Park

The comprehensive sampling of the inter-shoal and inter-reef parts of the study area revealed a high diversity of fish (we collected 340 species) and invertebrates (we collected 687 species or taxa). The inter-shoal area also has a diverse range of habitats ranging from relatively bare open sandy or muddy flats to highly diverse patches of reef. We divided the continental shelf into five distinct zones on the basis of sediment type, invertebrate and fish populations although there are not five discrete community types. Until the present study, the main focus of research and management has been on the reefs of the GBR and yet these make up only 5% of the GBR Marine Park. Nearly all of the research funding and effort on the GBR has therefore been applied to a minor part of the whole system. The extent of inter-shoal and inter-reef areas and their high diversity, requires that GBRMPA and the scientific community need to pay more attention to inter-shoal and inter-reef areas.

Although the Green Zone has been closed to fishing, including trawling, since 1985, we established that illegal trawling has occurred and continues to occur within the lagoon of the Green Zone; this has compromised the difference between the areas closed and open to fishing. There is little point in closing areas to fishing if the closures are not enforced. GBRMPA needs to work more closely with management and enforcement agencies to ensure that closures such as the Far Northern Green Zone are effectively policed. The introduction of VMS to the Queensland trawl fleet should substantially improve enforcement of closures for trawling.

Our comparison between the fauna of the area closed to fishing and the adjacent open areas failed to find any significant differences that could be unambiguously attributed to trawling. We have advanced four possible explanations for this. These are firstly that the level of illegal trawling in the closed area has been sufficiently high to blur any difference that may have arisen since the zone was closed. On the other hand, much of the open area is not trawled. Secondly, the level of natural variability was so high that it is difficult to detect a statistically significant difference, due to trawling, between the areas. Thirdly, the difference between the area to the south of the Green Zone and the area to the north was greater than between the Green Zone and these areas. This change in faunal composition also contributed to any differences that could be attributed to fishing. The fourth possibility is that a single pass of a prawn trawl has less impact than the power of the comparison (reduction to 41%). Thus the impact on the seabed cannot be detected especially if the level of effort in the open areas is low and there is trawling in the closed area. We have concluded that it is difficult to assess the impact due to trawling by comparing areas open to fishing with large closed areas if there is a high habitat and fauna diversity. This problem is exacerbated if the closed area is trawled and fishing effort in the open areas is low, as was the case with the study area for this project. This difficulty in using closed areas to estimate the impact of trawling would apply even if there were multiple closed areas in the GBR.

We carried out two experimental manipulations to test the effect of trawling. The first took the form of a BACI experiment in which plots were surveyed before being subjected to a single all over trawl Impact. The condition of the plots after the impact was then compared with unimpacted Controls. The BACI experiment showed that the impact of a single trawl in the northern GBR was not as severe as had been expected on the basis of observations on the North West Shelf of Western Australia. This difference is due to NW Shelf study targeting that part of the epibenthos that is most vulnerable to trawling, namely large sponges. The GBR study included all sponges including the many small encrusting types that are not as several impacted as the large upright forms. The GBR study also measured impacts on the full range of invertebrate groups as well as fish. The result is that the GBR experiment is a far broader study with information that has important implications for management.

The second experimental manipulation involved towing a trawl over the same track 13 times. It proved to be difficult to achieve but we established a cental corridor that was trawled at least 10 times and adjacent corridors with a lower impact. The Repeat-trawling experiment indicated that a single trawl removes 5 and 25% of the benthos depending on the species. This impact is far less than reported in the literature for beam trawls in the North Sea or scallop dredges and suggests that prawn trawls cause less damage than these heavier gears that tend to disturb the seabed to a greater extent. Repeated trawling however has a cumulative effect such that around seven trawls over the same ground will remove about half the benthos. There is an urgent need to study the rate at which communities recover from a trawl impact. If the rate is slow, then even low levels of effort repeated annually may eventually cause a serious impact. This is fundamental knowledge that is essential for sustainable management of the GBR inter-shoal areas. We have produced a model (See below) that attempts to integrate known information on depletion with theoretical rates of recovery to show the likely condition of the seabed benthos following a long period of closure.

Trawl effort is highly aggregated among 6 minute grids, with about 20% of the effort concentrated into <5% of trawled grounds (intensive) — at the other extreme, about 20% of the effort is spread over about 60% of the trawled grounds (extensive). Rigorous information on the spatial intensity of trawling within 6 min grids is only just becoming available, but that available from research in the NPF and from VMS suggests that trawling is also highly aggregated at very fine scales. The removal rates (resilience) of most seabed fauna was between 5–20% per trawl, but ranged up to 0–40% per trawl. The amount of fauna removed each year is related to the resilience of the fauna and the intensity of trawling. In lightly trawled grids, the annual removal may have been only a few percent, but in the most intensively trawled grids, more than 80% of the least resilient fauna may be removed each year. The average total annual removal of fauna from all trawled grids in the GBRMP may have been about 10% per year, but would be different for different fauna. About 4% of high resilience fauna may be removed, ~8% of medium resilience fauna, and ~15% of low resilience fauna. If fauna have no capacity for recovery, then eventually, all trawled seabeds will become completely denuded of fauna. With capacity for recovery, then all faunal vulnerability types have the potential for sustaining a population level in balance with the amount removed by trawling — up to a limit that is highly dependent on the intensity of trawling. The most vulnerable fauna may become 'extinct' in 5–10% of grids that are trawled with >2,000–3,000 hrs of effort; more fauna will become 'extinct' in grids with higher effort. Because of differential vulnerability, community composition will be substantially altered in most grids. The possible overall status of attached fauna after 20 years of trawling in all trawled grids in the GBRMP may be a depletion of ~20%, but would be different for fauna with different vulnerability's. Fauna with low vulnerability may be depleted by about 3%; medium vulnerability fauna may be depleted by about 20%; and highly vulnerable populations may be depleted by about 55% overall. Though 50-70% of trawled grids have been trawled only lightly (<700–1000 hrs) each year, over the last 20 years the cumulative effect of this has been that vulnerable types of fauna (ie. those easily removed and/or slow to recover) have been severely depleted. This has probably caused substantial changes in the composition of the faunal community, and the overall faunal biomass may have been reduced by ~20%, but it would be dominated by "weedy" species.

We found that trawling in the Far Northern Section resulted in large amounts of non-commercial bycatch that is discarded. If the results from our research trawls are extrapolated to commercial trawling, then average discards per trawler in the vicinity of the study area are around 750 –1100 kg each night. These figures must be treated with caution since they can be expected to vary seasonally and with the area fished. Nevertheless, the figures suggest prawn trawlers produce a large quantity of bycatch and most of this is discarded because it has little or no value. A variable proportion of these discards float and are available to surface scavengers, the rest sinks and is taken by benthic scavengers. Seabirds take only a minor proportion because most discards sink and of the fish that float, only half fall within the size range eaten by seabirds. The main scavengers of discards in inter-shoal areas are sharks and fish. The only species of seabird apparently affected by feeding on discards is the Crested Tern. Populations of this species have increased by two orders of magnitude over the time of the trawl fishery. This increase may have been the result of greater availability of discards for young birds. Despite the apparently limited environmental impact of discards, GBRMPA should support attempts by the fishing industry to reduce the amount of discards since this will reduce the impact of trawling on a wide range of non-target species.

7.4 East Coast management plan

The Queensland Fisheries Management Authority has produced a draft Proposed Management Arrangement for the Queensland Trawl Fishery East Coast and Moreton Bay for the period 1998-2005 (QFMA 1998). The results of the GBR Effects of Trawling Study has important implications for the management of prawn trawl fisheries and these are described below under the headings used in the Proposed Management Plan.

Effort Control and Reduction

According to the proposed Plan, it is proposed to cap the total effort at a level no higher than that applied in 1996. A method for reducing effort will be part of the new effort management system. Capping and eventually reducing trawling effort will reduce the extent of trawl impact on the seabed. It is possible that the reduction in effort may be greater on the marginal grounds and so will not be evenly spread. Thus we expect that heavily fished areas will continue to be targeted. Overall this will be a beneficial move. Heavily trawled areas have probably already reached a steady state of almost complete depletion and an increase in effort on them should not have any serious effect. This will probably be offset by a shift away from marginal areas as a fishing day becomes a more valuable commodity. The reduction in effort on marginal grounds should have a positive effect overall. The Plan presently does not mention the environmental benefits of reducing effort but it should do so.

Closures

The Plan proposes maintaining existing spatial closures as well as introducing large scale seasonal closures as part of the overall strategy for managing effort, maximising yield per recruit and reducing the catching of small prawns. The background to this section of the Plan also notes that one of the uses for closures is to minimise disturbance of selected marine environments and habitats for general conservation requirements. Despite this preamble, none of the management interventions address conservation and none of the proposed strategies are aimed at improving habitat management. The proposed seasonal closures would have little benefit in minimising environmental disturbances unless they result in a reduction in effort. The short duration of the seasonal closures – two and a half months each year – would not be long enough to provide significant recovery of benthic faunas impacted by trawling. If closures are put into place for environmental purposes, they should target structured, high value habitats. The matters of vulnerability, representativeness and adequacy also need to be addressed. The rate of recovery of habitats from trawling would need to be taken into account if temporal changes were used to benefit habitat.

Sustainability Indicators

None of the indicators proposed in the Plan are designed to ensure sustainability of the environment, they all deal solely with stocks. We recommend that sustainability indicators should also be developed for non-target habitat and indicator species and the information provided in the GBR Effects of Trawling Report will be helpful in this.

Fishing apparatus, gear restrictions and current regulations

The Plan proposes to reduce the total maximum effort in the fishery to sustainable levels. This is welcomed since any reduction will be helpful to seabed habitats. However, the sustainable levels referred to are for prawn stocks, not the environment and especially seabed habitat and bycatch. The results of the GBR Effects of Trawling study with respect to the impact of continued trawling and its effect on species composition together with the recovery times, show that sustainability of the seabed habitat must be taken into account.

The Plan also proposes to investigate the effect of ground gear on benthic habitat. This is welcomed although the proposed time frame (by 2000) is probably not realistic. No form of ground gear is likely to be environmentally friendly on structured habitats and so the fishery should be using the lightest feasible gear. The appropriate management intervention should possibly specify the maximum size or weight allowed. This offers a mechanism for reducing or even preventing trawling over structured habitat since trawling over rough seabed will damage light gear. This is costly to the operators who could be expected to avoid trawling in these areas. Most trawling takes place on soft seabeds and impacts are likely to be less than on structured seabed but this needs to be confirmed.

Species taken by trawling

This section of the Plan has two objectives that are important in the matter of the Effects of Trawling. Firstly it proposes to ensure that species taken by trawling are ecologically sustainable. Secondly, it seeks to minimise all impacts of trawling on non-target species. These objectives are welcomed. Of particular interest is Strategy 3 which is: To continuously reduce impacts of trawling on benthic communities.

The main management intervention to achieve the objectives is to introduce Bycatch Reduction Devices (BRDs) into the fishery. The introduction of BRDs will reduce the impact of trawls on many seabed animals. However, it is important to note that BRDs will not lessen the impact of trawls on sessile animals such as sponges. Strategies for addressing sessile animals need to be incorporated into the Plan with indicators or performance measures for these animals being decreasing amounts of bycatch and benthos taken.

Endangered or threatened species

Although no seabed species have been listed as threatened or endangered, the intention in the Plan to introduce TEDs will reduce the catch of large animals such as rays. Catches of these rays have declined considerably in many trawl areas overseas and so the introduction of TEDs is supported as being a positive move for many seabed animals.

Trawling takes a very large number of species – we collected hundreds of species of fish and invertebrates in prawn trawls in the Far Northern Section of the GBR It is not known whether any of these species are threatened by trawling. More information on this aspect of bycatch and trawl impacts is needed for the Queensland East coast on the lines of the research presently underway in the Northern Prawn Fishery (see 7.5 below) to establish whether such species exist and what management interventions are needed. It may be possible to protect them and prevent them from becoming Endangered or Threatened.

Enforcement, compliance and education

A major difficulty with the study of the Effects of Trawling has been that there has been an unknown amount of trawling within the area closed to fishing. We believe that lack of compliance is a common problem with regard to spatial closures and so we welcome the intention in the Plan to introduce VMS to East Coast trawlers. This offers the opportunity to improve enforcement of closures and make these a more effective management measure for protection of habitat. There is presently a large gap in our knowledge of the spatial pattern of trawling, VMS also offers an opportunity to close this gap which will increase understanding of likely impacts and how to minimise them. Given the practical limits on the amount and cost of VMS polling, it would be advantageous to stratify polling to optimise the information that can be gained. There is little point in obtaining large amounts of repeated position data from heavily fished areas and so the frequency of polling could be decreased in these areas. This saving could be directed towards lightly fished areas in order to obtain higher quality information on these areas. Maximum and minimum polling rates should be set to give the upper and lower bounds for a stratified polling strategy.

Data collection

We strongly support the intention in the Plan to provide more precise and accurate catch and effort data for management needs. There has been a considerable improvement in the quality of information on Queensland fisheries in recent years and continuation of this trend is welcomed. We strongly support the introduction of a 'research logbook' since this offers the opportunity to collect information that is of importance to researchers and management.

We strongly support the intention in the Plan to develop an improved bycatch database. There is however no mention of introduction of a system for validating logbook data; this needs to be done. Given the large size of the trawl fishery – around 850 trawlers – this may have to incorporate a sampling strategy.

Cost Recovery

We support the intention in the Plan regarding the introduction of cost recovery and putting funding for industry-oriented research on a sound base.

7.5 Where to from here

What aspects of the 1989 Workshop have been addressed by the trawling project

The 1989 Workshop recommended that high priority should be given to studies of the effects of fishing on the GBR. The Recommended Research Program was to address two aspects. Firstly the effects of trawling on the inter-reef areas and secondly the effects of line fishing and trawling on reefs. The latter project is presently underway but has been limited to examining the effects of line fishing largely because of funding constraints. The 1989 Workshop considered it unlikely that reductionist research would provide useful answers to effects of fishing questions at the scales with which we are dealing. The 1989 Workshop decided that a large scale experimental approach to the question was more appropriate. The 1989 Workshop also concluded that, at present, no realistic or useful experiment to investigate trawling effects in existing nearshore trawl grounds could be identified. It was considered that there is a lack of obvious connections with reef communities, it is difficult to close the substantial areas required for adequate investigation and there is uncertainty of what is being investigated. The 1989 Workshop concluded that the focus of the experiments should be on recreational and commercial handline fisheries and the red spot king prawn trawl fishery. The 1989 Workshop concluded that interactions between the trawl fishery and reef communities, if they are significant, are likely to be found in the red spot king prawn fishery because the juveniles are found on reefs and trawling for adults occurs near and between reefs.

The Effects of trawling study was to replicate the impact of trawling and fate of discards investigation carried out by CSIRO in Torres Strait. Subject to adequate surveillance and enforcement of the Marine National Park (MNPB) Zone in the Far Northern Section of the Great Barrier Reef Marine Park, the 1989 Workshop recommended that the study be repeated north, south and inside the MNPB transect. A three year study would provide a replicate of the Torres Strait results to assess their generality and provide a GBR study of trawled and 'recovering' areas. The three year study was to focus on the impact of trawling on benthic systems, recovery of the benthic communities in the MNPB and the fate of discards from the fishery.

The CSIRO-QDPI Effects of Trawling study that was subsequently developed after extensive consultation with GBRMPA, has focussed on the MNPB – later referred to as the Green Zone. The CSIRO Torres Strait study was largely limited to describing the composition of the bycatch with some work on the fate of discards. It did not attempt to examine the impact of trawling on the seabed habitat. GBRMPA made it clear that this was to be an important aspect of the new study and so a large proportion of the effort was put into this. The extent of trawling within the Zone has been estimated but because trawling there is illegal, it has not been possible to quantify it exactly. In addition a major investigation was carried out to compare the fauna within the area closed to trawling with that outside. As pointed out above, the major conclusion is that the differences between different parts of the area open to fishing are at least as large as those between the area closed and the area open. While GBRMPA may declare other Green Zones in the GBR for conservation purposes, this will probably not be a suitable approach to determining the effects of fishing because of the scale of natural differences between various areas. The CSIRO-QDPI study did adopt the large-scale experimental approach recommended by the 1989 Workshop and a BACI and a repeat trawl experiment were carried out. These showed that the figure of a 90% impact of a single trawl current at the time of the 1989 Workshop was both an overestimate and did not reveal the complexity of the impact of trawling. The experimental studies showed that the overall impact of a single trawl pass varied between 5 and 20% and varied between taxa. The result of repeated trawling is to deplete the seabed fauna differentially. Thus there is a shift in species composition, which may have far reaching ecological effects. Discards were found to have less impact than was supposed. Only one species of seabird showed population changes although several were found to feed on discards.

The experiments reported here were not designed to answer questions about past effects in previously trawled grounds on soft sediments of the main lagoon, and especially the effects of trawling on smaller infauna. These lagoonal soft-sediment fauna may, however, be less vulnerable to trawling. Because the intensity of trawling and the effects in soft sediments are poorly known, the overall impact of trawling on the GBR ecosystem is not yet fully clear. To determine whether the effects of trawling on benthos are small enough to be ecologically sustainable, more information is required on the distribution and dynamics of benthos communities, the spatial distribution and intensity of prawn trawl effort (at much finer scales than are presently collected) in the GBR region, and the vulnerability of soft-sediment fauna.

Clearly, prawn trawling can degrade the state of the inter-reefal benthos and, despite the absence of long-term data sets to confirm trends, anecdotal reports, circumstantial evidence, these research results and their extension suggests that there have indeed been changes. The experiments reported here showed that the cumulative effect of high intensity prawn trawling is likely to be substantial on epibenthos in species-rich offshore areas, but that the effects may not be detectable in extensive areas that are trawled infrequently or sparsely. This result is important because the intensity of trawling is not uniform; some areas are trawled intensively, but large areas are trawled only occasionally or sparsely.

Overall, the CSIRO-QDPI study has accomplished far more than the participants at the 1989 Workshop had hoped by proposing a replication of the Torres Strait study – which would have covered a far narrower scope. It has addressed the difficult problem of impacts of trawling on a complex and little known environment. It has used a range of powerful techniques to obtain robust data and it has synthesised this into a model that explains the likely impacts of trawling on a range of seabed taxa. Finally, it has provided managers with an assessment of the implications of the research.

Future Research

Although the GBR Effects of Trawling has been a major project that has provided important information for managers, it would be unrealistic to expect that it will provide all of the answers to the questions surrounding the effects of trawling on seabed habitats. The project did not for example, deal with recovery rates and yet these are essential in predicting the impact of trawling. The project also did not deal with soft bottom communities and the results should not be extrapolated to them. It is important to recognise that inter-reef and inter-shoal areas including the inner and outer lagoons, occupy around 95% of the area of the GBR. Despite this dominance, nearly all of the research carried out on the GBR during this century has dealt with the more prominent but vastly smaller scale coral reefs. There are a range of reasons for this including accessibility, the greater public profile of reefs and the bias of funding bodies and researchers. Several key questions remain regarding the effects of trawling and need to be addressed. The GBR Effects of Trawling project has already had flow on effects in generating research into seabed habitats and the following projects have all commenced since the start of the GBR project:

1. *Recovery monitoring*

This is being carried out on the tracks used in the Repeat Trawl depletion experiment in which between 70 and 95% of the initial biomass of attached seabed fauna was removed. The objectives of the project are to document the recovery of seabed fauna after the depletion experiment by assessing the vulnerable species or taxa; the physical structure; and community complexity and measuring their recovery 1, 2 and 4 years after the impact. Non-destructive sampling tools are essential so as not to interfere with the recovery of the study area. Further, because the study sites are too deep for diving, recordings of remote video observations (from the ROV and video sled) of the seabed habitat of the study area are being used. Accurate position locating equipment is being used that allows Benthic fauna to be located with precision of better than 2 m. The species, position, size and condition of all identifiable sessile megabenthos are recorded at each site. Data is analysed for population density, nearest-neighbour distance, height, width, area, percentage missing, and percentage dead of organisms Power analysis was conducted for each variable to estimated minimum detectable recovery rates and minimum detectable differences between trawled tracks and controls.

2. *Bycatch sustainability*

CSIRO with financial assistance from FRDC, is carrying out a study of ways to assess bycatch sustainability in tropical prawn trawl fisheries. This is being done in two ways:

1. Assessing whether species found on trawl grounds and so vulnerable to being trawled, are also found off trawl grounds. This work is being done in the Northern Prawn Fishery. The species composition is being determined of bycatch from areas presently being trawled commercially and those in adjacent waters that have been closed to trawling, but are otherwise similar habitats.

2. Estimation of the vulnerability of bycatch species to prawn trawling. This is a function of the following:

    - The proportion of the biomass of the population of each species that is vulnerable to prawn trawling. Factors in this are the occurrence/status of populations outside heavily fished areas; identifying which size classes are susceptible to trawling; comparison of day versus night catchability and identification of behaviour that may provide substantial protection from trawling.

- The size at first maturity compared to the sizes that are caught by trawling.
- The fecundity (number of eggs per reproducing female) of species that are vulnerable to prawn trawling and timing of the breeding season compared to the time of impact by trawlers.

Resilience/vulnerability factors are being compiled for each species in the bycatch. This will allow the vulnerability of each species to trawling to be assessed. This study will be completed in June 1999.

3. *Methods for monitoring bycatch*

The introduction of a range of techniques for reducing bycatch requires an accurate method for monitoring the quantity and composition of bycatch. CSIRO with support from FRDC, is presently comparing three different systems for monitoring bycatch of prawn trawlers in the Northern Prawn Fishery. The first system is to have vessels record their bycatch. The second is for vessels to collect samples of bycatch and for these to be analysed by qualified staff on shore. In the third system observers on a subset of commercial vessels would record quantities of bycatch at sea and collect samples for onshore analysis. These three different methods have increasing reliability but increasing cost and one of the aims of the study is to carry out a cost-benefit analysis in order to provide guidance in establishing the lowest cost system than will provide data of the required accuracy.

4. *Dynamics of large sessile seabed fauna*

A study by CSIRO with support from FRDC. The research is being carried out on the GBR in the Townsville region and is measuring the recruitment, growth, mortality and reproduction of structurally dominant large seabed organisms (sponges, gorgonians, alcyonarians and corals). The information will be used to model the dynamics of seabed habitat and predict the potential of trawled grounds to recover. The project is documenting the usage of this habitat by key commercial finfish species. Three fishery-independent and environmentally friendly techniques for surveying tropical finfish resource abundances in inter-reef areas are being trialed and compared. A linked CSIRO-funded study will measure the effect of water current on recruitment and growth of megabenthos in Moreton Bay.

In addition, several new research projects are now being developed, these include:

1. *Impacts of trawling on soft sediment communities*

The GBR study was focused on seabeds having a three dimensional structure. It did not deal with the impacts of trawling on soft sediment fauna and should not be extrapolated to soft sediments. Most trawling in Queensland is over soft bottom sediments and so a new project is proposed that would specifically target these communities. This would be a far smaller scale project than the GBR study of the effects of trawling and take advantage of several long standing closures that have been adequately enforced.

2. *Mapping of seabed habitats of the GBR*

An NHT proposal has been developed to extend the results of the CSIRO/QDPI "Effects of trawling" study to the rest of the GBR. This will ensure sufficient representative latitudinal transects of the GBR have been documented to adequately describe the biodiversity and ecosystems of the soft bottom lagoon and inter-reef. The resulting information will provide a rigorous information-base to underpin future representative-area based management of the GBR World Heritage Area. It is not possible to effectively manage the biodiversity of an area of unique World importance if the resources of 95% of that area are unknown.

Three broad-scale surveys are planned, one each in the areas Cooktown-Cairns in the northern section (~16°S), Bowen-Mackay in the central section (~20°S), and off Shoalwater Bay in the southern section (23°S). Each broad-scale survey would be from the near-shore to the outer barrier reef and would encompass 10,000 - 20,000 km^2. Up to 200 sample sites located in a stratified representative pattern will give an adequate compromise between statistical rigour and the logistics required. The stratification will be based on the spatial distribution of known environmental correlates, such as depth, sediments, and current-stress that have proved significant in other regions (eg. Torres Strait). Samples will be collected by a 12 fathom otter trawl (~1 n.mile tow), 1.5 m benthic dredge (~300 m tow), sediment grab (0.1 m^2), remote video camera (500 m tow), and by acoustic remote sensing (continuously) at each site.

The distribution and abundance of seabed habitats and biodiversity of associated flora and fauna will be recorded together with environmental factors most likely to influence seabed habitat and species distribution and abundance. The information will provide maps of the distribution of seabed habitats and biological community types as the necessary first step for representative-area based management. A consortium of CSIRO, QDPI, GBRMPA, QDoE, and the Queensland Museum will carry out the work.

Conclusion

The information derived from the GBR Effects of Trawling Project and that coming from the flow-on research and proposed research, will enable the management and sustainability of the seabed habitat to be put onto a sustainable basis for the first time. When combined with technological improvements to trawl gear and handling techniques, we can expect to see the environmental impact of trawling to be considerably reduced in the future. This will make the fishery sustainable not only for prawns but also for the many animals that make up the total environment of a prawn fishery.

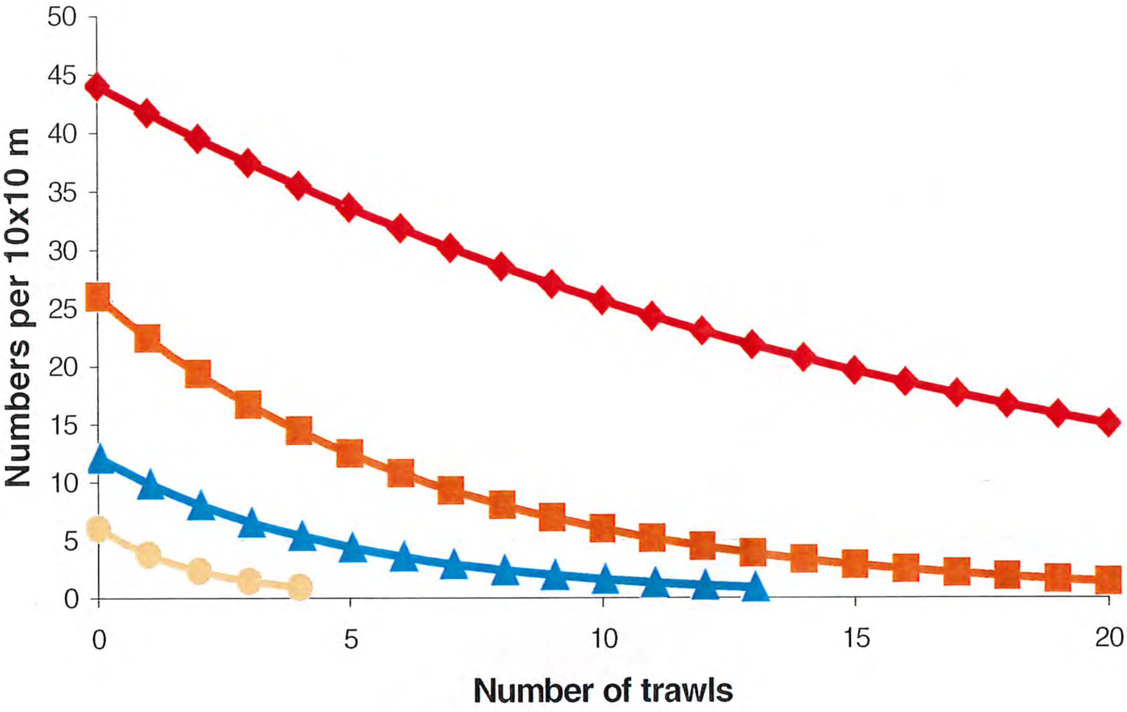

Figure 7.01 Examples of the resilience of four different attached fauna (◆ = Sea whip (Gorgonacea: *Junciella*), ■ = Sea fan (Gorgonacea: *Ctenocella*), ▲ = Fan sponge (Porifera: *Ianthella*), ● = flower pot coral (Zoantharia: *Turbinaria*) shown as an average rate of depletion (respectively: 5.2%, 13.7%, 18.6%, 37.6%, per trawl) from average un-impacted densities in patches of epifaunal habitat in the Green Zone (source CSIRO/GBRMPA Recovery Dynamics Project unpubl. data).

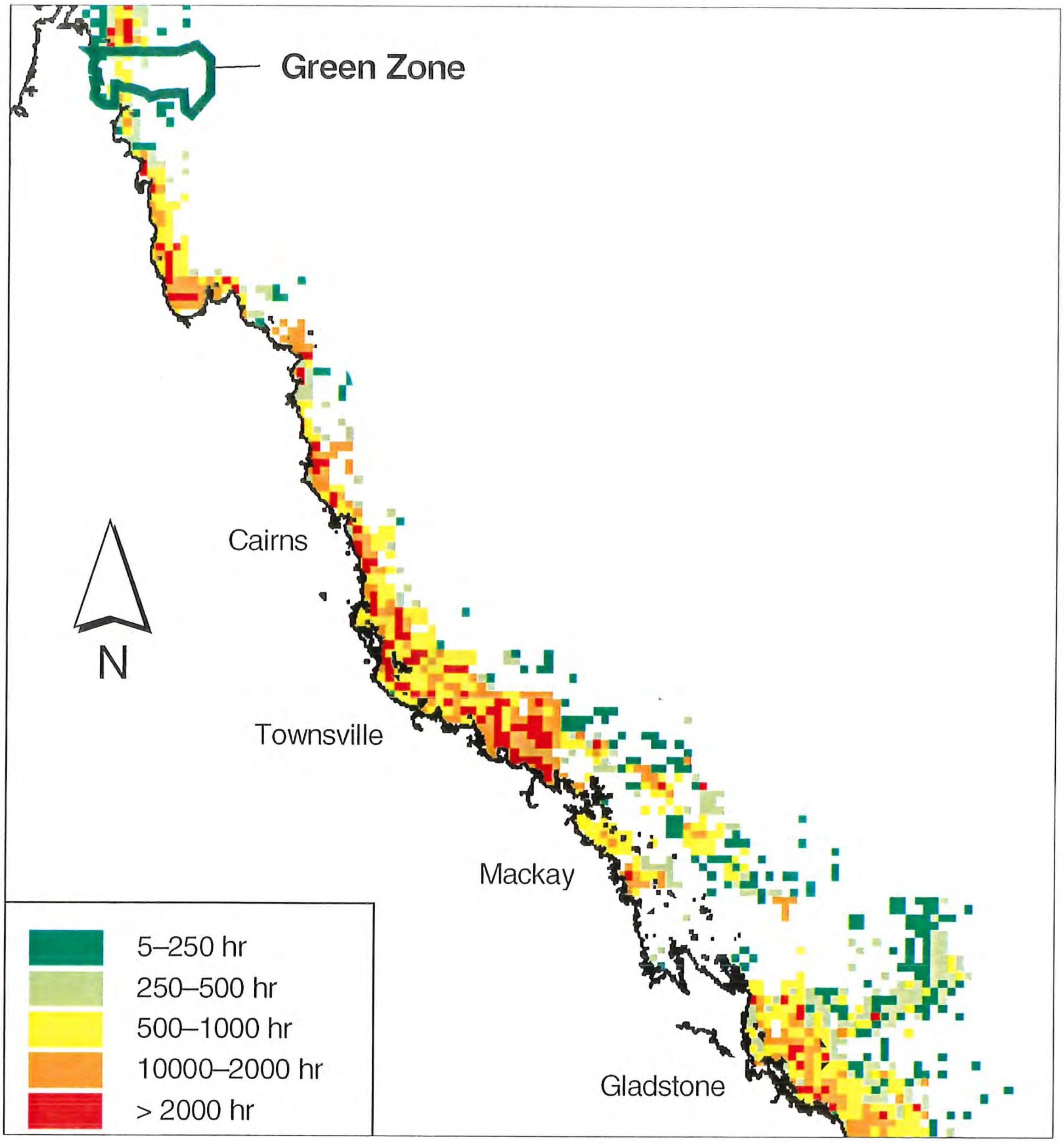

Figure 7.02 Distribution of 1996 trawl effort in the Queensland Trawl Fishery based on re-interpretation of 30 min grid logbook records into 6 min grids, using research logbooks recorded by 30% of the fleet (source Francis Pantus, GBRMPA unpubl.)

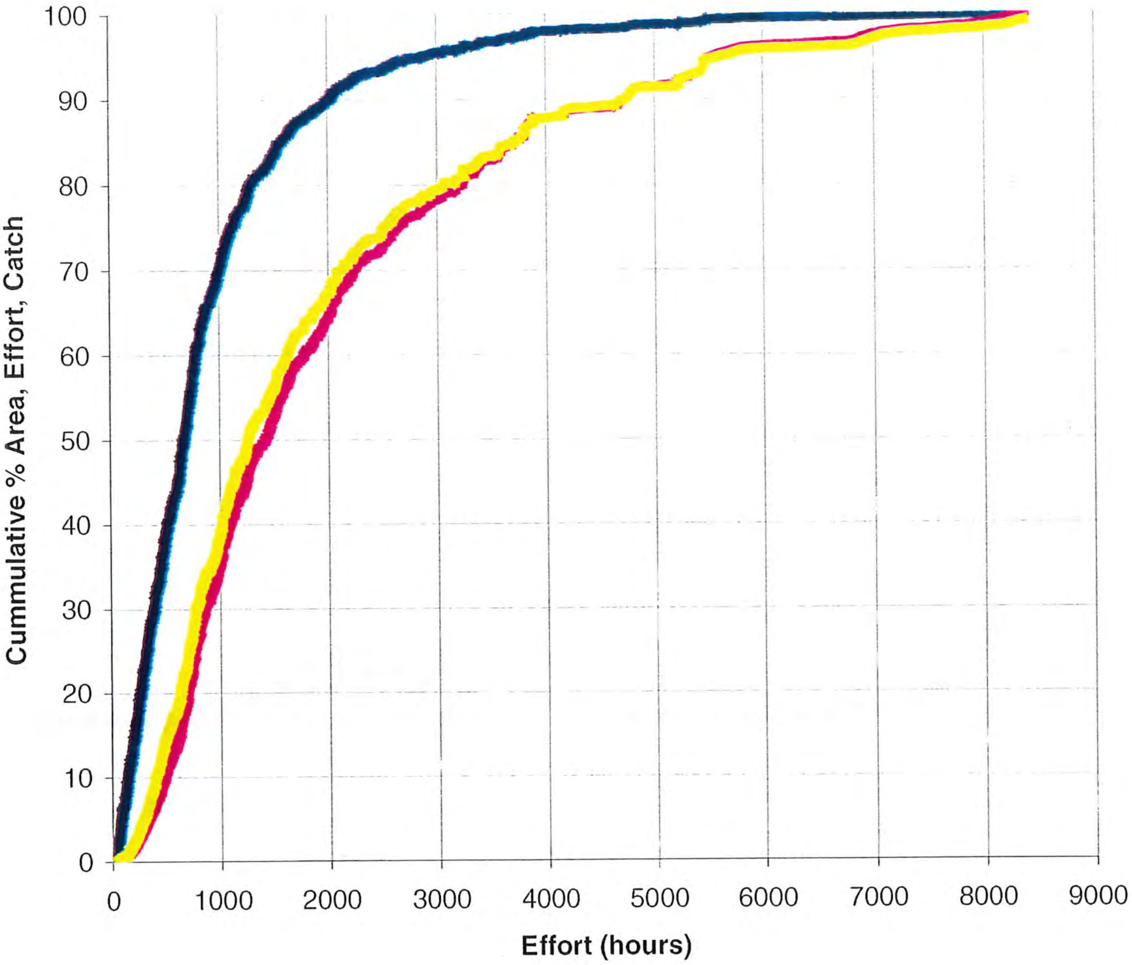

Figure 7.03 Cumulative distribution curves of 1996 trawl grid area (—), catch (—) and effort (—) in the Queensland Trawl Fishery based on re-interpreted 6 min grid data (source Francis Pantus, GBRMPA unpubl.)

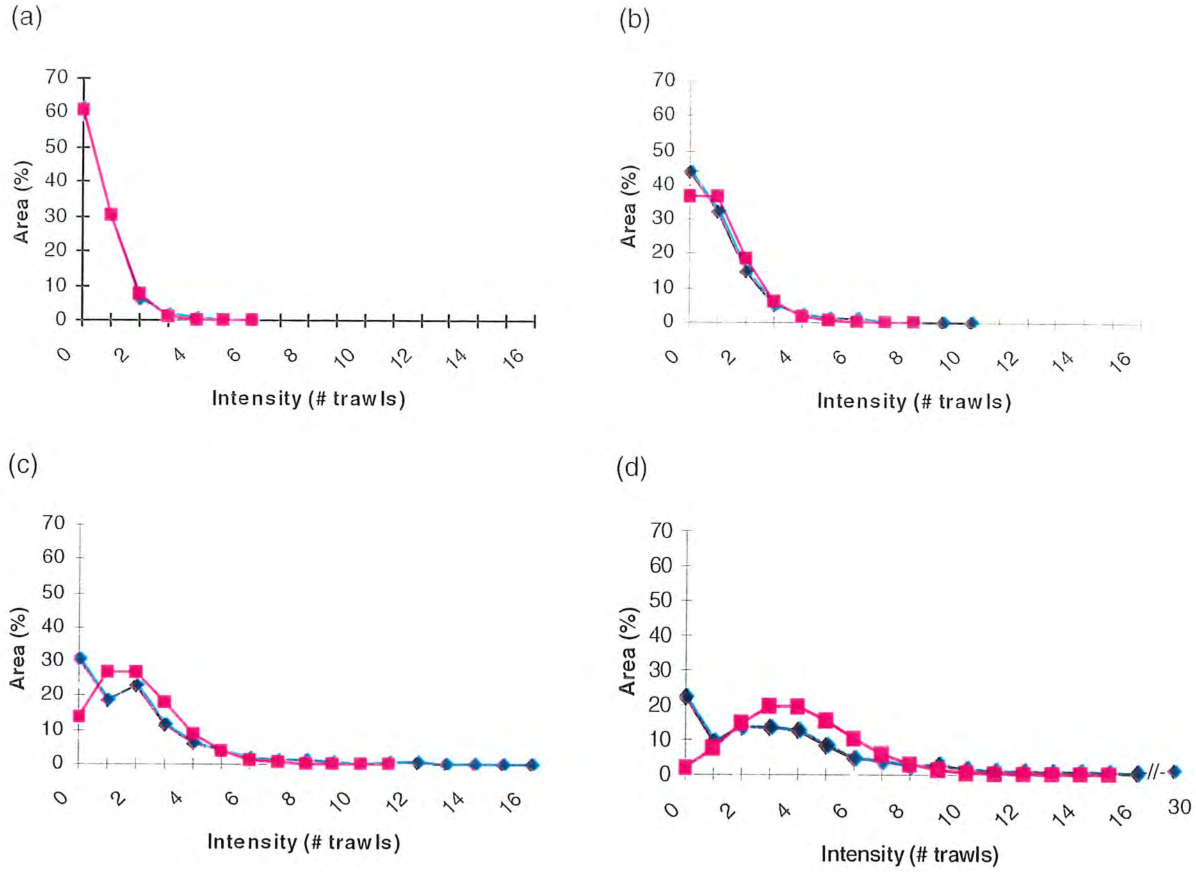

Figure 7.04 Frequency distribution curves for the intensity of trawling on 30 m pixels within 6'x6' grids trawled at different overall intensities for a random (■) and aggregated (◆) distribution of effort (a) = 500 hrs, (b) = 1000 hrs, (c) = 2000 hrs & (d) = 4000 hrs.

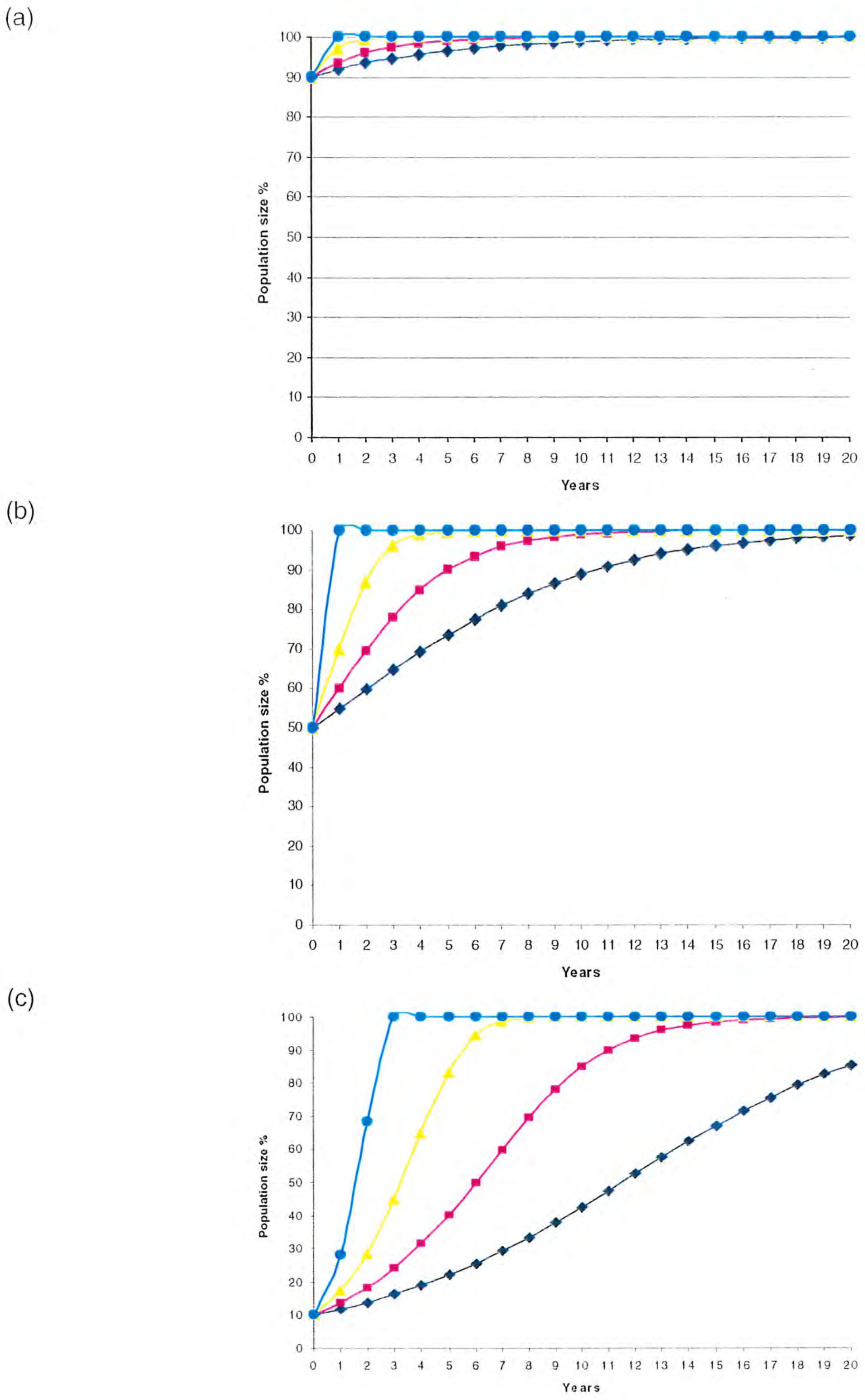

Figure 7.05 Illustration of the logistic population growth model for four different faunal types having growth coefficients ◆=0.2, ■=0.4, ▲=0.8, & ●=2.0, and for (a) 10%, (b) 50% and (c) 90% impact. Maximum population growth occurs when the population is at half carrying capacity (b). Recovery times are dependent on the extent of the impact, even though the population growth coefficients are the same in each case.

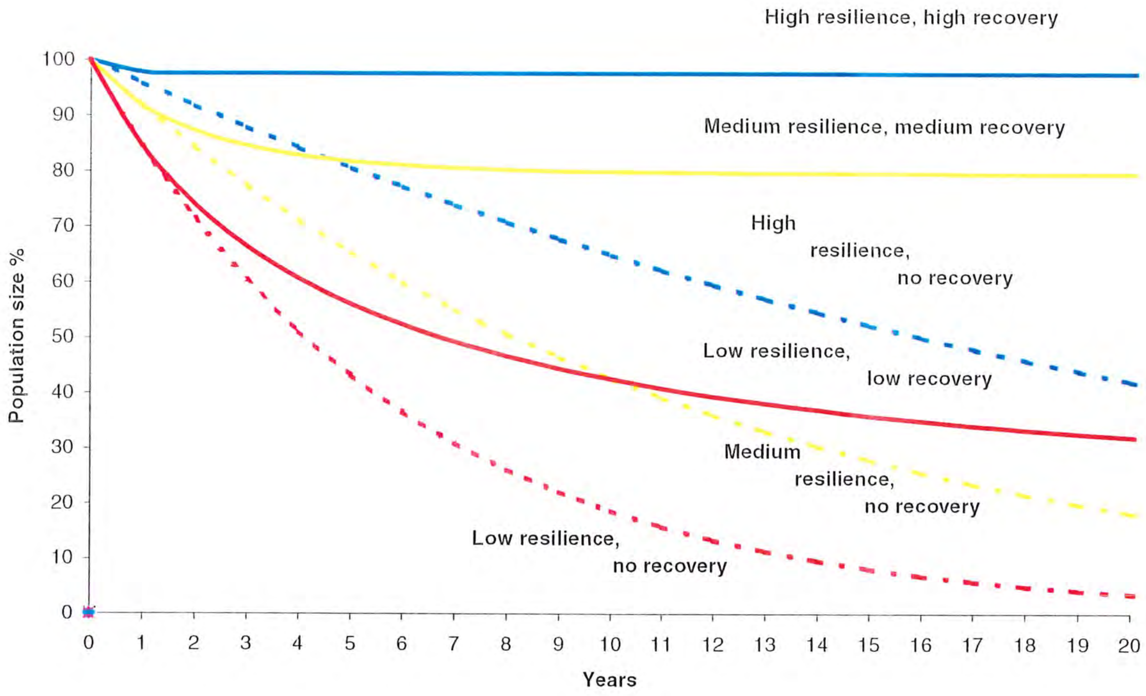

Figure 7.06 Time trajectories for depletion of fauna of different resilience (high, medium & low = 5%, 10% & 20% removal per trawl) with no capacity for recovery (- - - - -) and with high (r=2.0), medium (r=0.8) & low (r=0.2) recovery dynamics respectively (——), in a grid subject to an average level of trawl effort (~700 hrs).

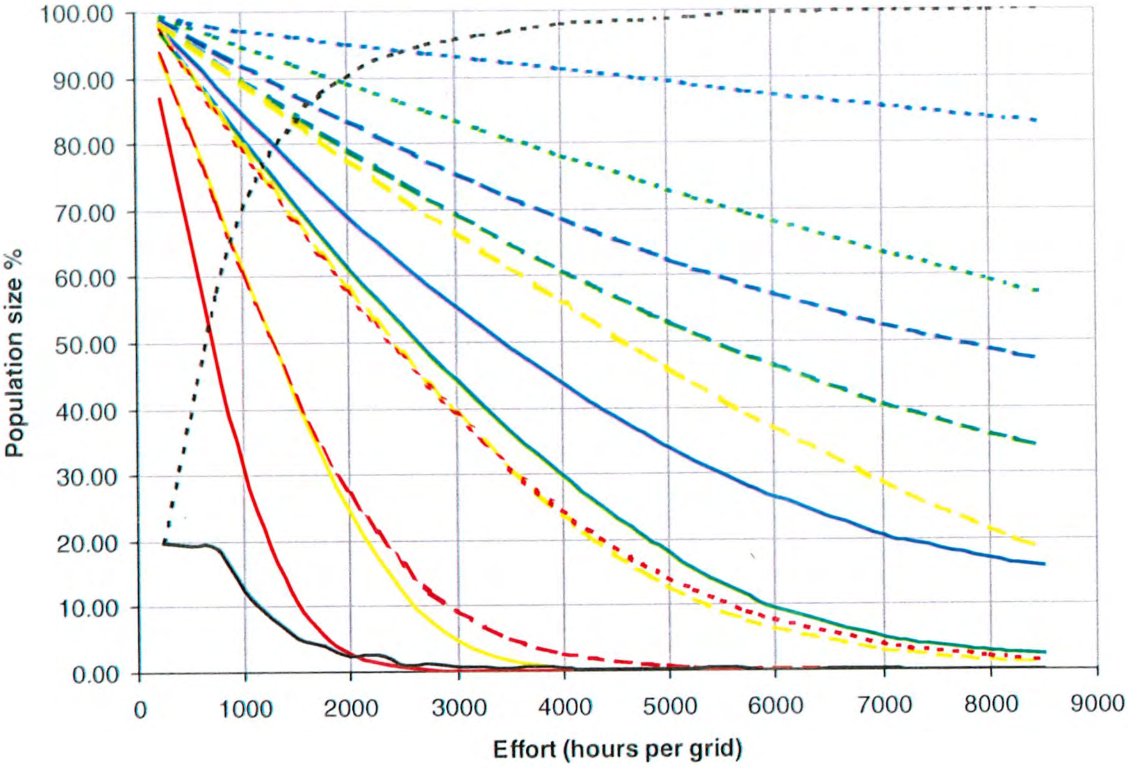

Figure 7.07 Population status of 12 different faunal types after 20 years of trawling in grids trawled with different levels of effort. Fauna of different resilience (high - - - -, medium — — & low ——, = 5%, 10% & 20% removal per trawl) and with high (r=2.0), medium-high (r=0.8), medium-low (r=0.4) and low (r=0.2) recovery dynamics. The percent frequency (——) and cumulative (• • • •) distributions of effort intensity in grids are also shown.

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APPENDIX

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B.2 Papers accepted and in press

Wassenberg TJ, Burridge CY, Connel M, Gribble N (1998). A validation of short-duration scientific tows as a representative of long commercial-length tows: comparing the catch rates, size composition and species composition of prawn trawler bycatch in the far northern Great Barrier Reef, Australia. *Fisheries Research*

B.3. Papers in preparation

Burridge, CY, Pitcher R and Gribble NA. Is it feasible to assess the impacts of prawn trawling on seabed fauna by comparing areas open and closed to fishing: an experiment in the Far Northern Section of the Great Barrier Reef Marine Park.

Brewer D, Blaber SJM, Burridge CY, Wassenberg TJ, Gribble N and Pitcher R. Distribution and abundance of inter-reef fish communities of the Far Northern Section of the Great Barrier Reef, Australia.

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Pitcher R, Burridge CY and Wassenberg TJ. Description of the benthos of the Far Northern Section of the Great Barrier Reef

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C. REPORTS PRODUCED DURING THE COURSE OF THE PROJECT

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