Bycatch weight, composition and preliminary estimates of the impact of bycatch reduction devices in Queensland's trawl fishery

A. J. Courtney, J. A. Haddy, M. J. Campbell, D. P. Roy, M. L. Tonks, S. W. Gaddes, K. E. Chilcott, M. F. O'Neill, I. W. Brown, M. McLennan, E. J. Jebreen, C. van der Geest, C. Rose, S. Kistle, C. T. Turnbull, P. M. Kyne[1], M. B. Bennett[1] and J. Taylor[2]

Queensland Department of Primary Industries and Fisheries
[1]Department of Anatomy and Developmental Biology, University of Queensland
[2]Australian Maritime College

Queensland Government

Australian Government
Fisheries Research and
Development Corporation

Project No. 2000/170

PR07–2868

Bycatch weight, composition and preliminary estimates of the impact of bycatch reduction devices in Queensland's trawl fishery.

A. J. Courtney, J. A. Haddy, M. J. Campbell, D. P. Roy, M. L. Tonks, S. W. Gaddes, K. E. Chilcott, M. F. O’Neill, I. W. Brown, M. McLennan, J. E. Jebreen, C. Van Der Geest, C. Rose, S. Kistle, C. T. Turnbull, P. M. Kyne, M. B. Bennett and J. Taylor

Report to the Fisheries Research and Development Corporation

Project No. 2000/170

May 2007

This report provides quantitative information on the effects of turtle excluder devices (TEDs) and bycatch reduction devices (BRDs) on the catch rates of bycatch, prawns, scallops and byproduct species, such as Moreton Bay bugs and Balmain bugs, in Queensland’s major trawl fishing sectors. It also provides biological information on, and management advice for several species referred to in the Fishery Management Plan as the permitted species. Several recommendations are included for reducing bycatch in the trawl fishery and for sustaining stocks of the permitted species.

The Department of Primary Industries and Fisheries (DPI&F) seeks to maximise the economic potential of Queensland’s primary industries on a sustainable basis.

This publication has been compiled by A. J. Courtney of Sustainable Fisheries.

Table of contents

List of Tables

List of Figures

2000/170 Bycatch weight, composition and preliminary estimates of the impact of bycatch reduction devices in Queensland's trawl fishery

PRINCIPAL INVESTIGATOR: Dr A. J. Courtney
ADDRESS: Queensland Department of Primary Industries and Fisheries
Southern Fisheries Centre,
PO Box 76
Deception Bay QLD 4508
Telephone: 07 3817 9582 Fax: 07 3817 9555

1 Objectives

1) Describe the bycatch species composition and catch rates under standard trawl net conditions [non-Turtle Exclusion Devices (TEDs) and non-Bycatch Reduction Devices (BRDs)] in Queensland’s major trawl sectors (eastern king prawn, scallop and tiger/endeavour prawn sectors).

2) Describe the bycatch species composition and catch rates when nets have TEDs and BRDs installed in Queensland’s major trawl sectors (eastern king prawn, scallop and tiger/endeavour prawn sectors).

3) Test and quantify the impact of different combinations of TEDs and BRDs on bycatch and target species against standard nets under controlled experimental conditions using chartered commercial trawlers in the eastern king prawn, scallop and tiger/endeavour prawn sectors.

4) Review the known biology and distribution of all recently approved “permitted fish” species associated with the trawl fishery.

5) Quantify key population parameter estimates, including growth rates, size at maturity, distribution and landings, for all recently approved “permitted fish” species.

6) Apply power analysis to determine how many samples are needed to detect various levels of change in bycatch species catch rates.

7) Provide advice on the guidelines and definitions of BRDs and TEDs so that the Boating and Fisheries Patrol can confidently enforce the regulations.

2 Non-technical Summary

OUTCOMES ACHIEVED TO DATE

- All stakeholders, including the Queensland Fishery Managers, conservation agencies, industry, recreational fishing groups, the public, the Great Barrier Reef Marine Park Authority (GBRMPA) and DEH, are in a much more informed position to comment on how well the fishery management initiatives are reducing bycatch, and perhaps what more needs to be done.
- Greatly improved understanding of the catch rates and composition of bycatch in each of the major trawl fishery sectors.
- More fishers are using highly effective square mesh codends in the scallop and eastern king prawn fisheries as a result of the project.
- The project demonstrated that bycatch rates in the scallop fishery can be reduced by 77% if square mesh codend BRDs are made mandatory in this sector with TEDs. This large reduction can be achieved with no loss of marketable scallops and with 63% fewer undersize scallops being caught.
- Improved understanding of the impacts of trawling on species of high conservation or recreational value.
- The project showed fishers and managers how to reduce the incidental catch rate of stout whiting caught in prawn trawl nets by 57%.
- Greatly improved understanding of the elasmobranch bycatch in the trawl fishery, and the effects of TEDs and BRDs upon them.
- Stakeholders are in a more informed position to determine whether the bycatch composition in each of the major sectors is likely change as a result of TEDs and BRDs.
- The accuracy of standardised catch rates and stock assessments for prawns, scallops and bugs has improved because the project quantified the effects of TEDs and BRDs on them.
- Queensland fishery managers are in a stronger position to discuss the value of bycatch monitoring programs, to decide upon their implementation and to provide input to their design.
- Through the project staff involvement with the Technical Working Group, the design and specifications of BRDs has been improved.
- Through project staff interaction with the Boating and Fisheries Patrol, patrol officers are more informed about TED and BRD design specifications and functions. The Patrol are in a stronger position to police and enforce the devices.
- The yield and value of three spot crabs *Portunus sanguinolentus* has improved and the likelihood of overfishing this stock is reduced as a result of the project.
- Managers have an improved understanding of the distribution and composition of Balmain bug (*Ibacus* spp.) and mantis shrimp landings in Queensland.
- Reduced likelihood of overfishing Balmain bugs, as a result of the minimum legal size advice as a direct result of the project.
- Information obtained on the distribution of the pipehorse (*Solegnathus* cf. *hardwickii*), which is listed as vulnerable on the IUCN Red List, can be used to conserve populations of this species.

The project provided quantitative biological and technical information on two issues relating to the Queensland trawl fishery:

1) the assessment of TEDs and BRDs on the catch rates of bycatch, target species and bycatch community structure in the main trawl sectors, and
2) the biology, population dynamics and management of several species that are caught incidentally in the fishery that can now be retained and marketed.

> These species are listed in the Trawl Fishery Management Plan [*Fisheries (East Coast Trawl) Management Plan 1999*] as the permitted species and include barking crayfish (*Linuparus trigonus*), Balmain bugs (*Ibacus* spp.), three spot crabs (*Portunus sanguinolentus*), mantis shrimps, (Stomatopoda), cuttlefish (*Sepia* spp.), octopus (*Octopus* spp.), pipehorses (*Solegnathus* spp.) and Pinkies (*Nemipterus* spp.).

Evaluating the performance of TEDs and BRDs
The project obtained 1619 measurements and sub-samples of bycatch during a) dedicated research charters that were designed to test TEDs and BRDs, and b) opportunistic sampling on board commercial vessels during their normal fishing activities. A total of 49.1 tonnes of bycatch was weighed at sea, of which 9.8 tonnes was sub-sampled and processed to species level in the laboratory. Over 1300 taxa were recorded in the bycatch, including records of new species occurrences in Queensland, and new information on the extent of species' distributions.

Information is provided on the a) bycatch species composition in each major sector of the fishery and their catch rates, b) effects of TEDs and BRDs on the catch rates of prawns, scallops, byproduct species (i.e., Moreton Bay bugs and Balmain bugs), total bycatch and individual bycatch species, including the elasmobranchs (sharks and rays), and c) bycatch community assemblages and how they vary with latitude, depth and BRD type.

Research charters
The most promising finding from the project was obtained from one of the research charters which demonstrated that bycatch rates in the saucer scallop fishery could be reduced by a mean of 77% by using nets with both TEDs and square mesh codend BRDs, compared to standard nets. Importantly, this reduction was achieved with no reduction in the catch rate of legal size scallops, and with 63% fewer undersize scallops being caught. For these reasons we recommend that square mesh codend BRDs be made compulsory in the scallop fishery. (TEDs are already compulsory in all trawl sectors, but fishers can use less effective BRDs). If all scallop fishers used these devices, it would equate to a reduction in bycatch of over 10,000 tonnes annually compared to pre-2000 levels (i.e., before TEDs and BRDs were introduced). Use of the square mesh codend BRDs is likely to lower the incidental fishing mortality on undersize scallops, and possibly increase the available exploitable biomass.

The project also demonstrated high potential for square mesh codend BRDs with TEDs in the deepwater eastern king prawn fishery, where the mean bycatch rate was reduced by 29%, with no loss of targeted prawn catch. For this reason, we also recommend the mandatory use of square mesh codend BRDs in this sector.

Another 10-night charter undertaken in the shallow water eastern king prawn fishery demonstrated a significant reduction in mean bycatch rate of 24% by using a radial escape section BRD and TED, compared to a standard net. This combination of devices was particularly effective at reducing catch rates of bentho-pelagic species with fusiform body shape, such as stout whiting *Sillago robusta* (57% reduction) and yellowtail scad *Trachyurus novaezelandiae* (32% reduction). Unfortunately, the mean catch rate of marketable size eastern king prawns was also reduced by a mean 20%

during the charter, mainly via the TED. The charter showed high potential application for the radial escape section BRD in the shallow water eastern king prawn fishery. We believe the prawn loss could be largely mitigated by adjusting the angle of the TED.

The radial escape section BRD and TED were also evaluated in the north Queensland tiger/endeavour prawn fishery during an eight-night charter. While a significant 20% reduction in mean bycatch rate was demonstrated, it was concluded that the radial escape section BRD was less effective in this sector because a) the bycatch fish species were generally smaller than those of the eastern king prawn fishery and therefore less capable of swimming to, and escaping out of, the device, and b) trawl speed is higher and codends are longer in the tiger/endeavour prawn fishery, thus making it more difficult for small fish species to swim forward and out of the device. The results show that one BRD type is not suitable for all sectors of the fishery, that each sector has its own unique bycatch properties and that effective BRD usage needs to be tailored to each sector.

Opportunistic measures on board commercial vessels
Analysis of the opportunistic sampling obtained on board commercial vessels during their normal fishing activities indicated that, across the major prawn trawl sectors (i.e., north Queensland tiger/endeavour prawn, and shallow- and deepwater eastern king prawns sectors) there was no statistically significant reduction in total mean bycatch rate (i.e., all bycatch including large sharks, large rays and large sponges known collectively as “monsters”) due to TEDs and BRDs, compared to standard nets. When analyses were undertaken excluding large fauna, the mean bycatch rate (i.e., excluding monsters) was significantly reduced by 25%, when both TEDs and BRDs were installed. The reduction in bycatch rate due to the TEDs and BRDs that were used by commercial fishers was low compared to those obtained during the research charters. Reductions in bycatch rates were greater in the tiger/endeavour prawn fishery, while no significant reductions were detected for devices being used in the shallow- and deepwater eastern king prawn sectors. No significant effects on marketable prawn catch rates were detected for the devices being used by industry. In the saucer scallop fishery, the TEDs and BRDs that were being used by fishers resulted in a reduction in total mean bycatch rate (i.e., includes monsters) of 68%. This reduction was due mainly to TEDs excluding large sponges which dominate the bycatch weight in this sector. A significant reduction in scallop catch rate of 11% was detected and mainly attributed to BRDs.

Bycatch reduction could be improved in the Queensland trawl fishery by a) promoting regular meetings of the Technical Working Group which was formed to evaluate BRDs and improve upon their technical specifications, b) further research and testing of BRDs, c) workshops with fishers that demonstrate and promote the more effective devices, d) educational programs for the Boating and Fisheries Patrol to enhance enforcement of the devices, and e) incentives for fishers to reduce their bycatch.

Biology and management of the permitted species
The project provided information on the biology, distribution and management of the permitted species. New information is provided on the species composition of Balmain bug landings in Queensland; the garlic bug *Ibacus chacei* constitutes the majority of Balmain bug landings, followed by the honey bug *Ibacus brucei* and the velvet bug *Ibacus alticrenatus*. The project provided a clearer understanding of the

distribution and fishery for these species, as well as an improved understanding of the growth rates of *I. chacei* and the size, age and location at which it reproduces. Minimum legal sizes for Balmain bugs were developed and recommended to the fishery managers. The first detailed description of the reproductive biology, distribution and fishery for the little-known barking crayfish *Linuparus trigonus* is provided. We also recommended a minimum legal size of 80 mm CL for barking crayfish. The reproductive biology and growth of three spot crabs *Portunus sanguinolentus* were described and a minimum legal size of 100 mm CW was recommended and adopted, based on yield-per-recruit analysis. The project provided new information on the distribution and reproductive biology of mantis shrimps in Moreton Bay, where the majority of mantis shrimp reported catch is taken. New information on the catch rates, distribution, sizes and faunal community associations for the pipehorse, *Solegnathus* cf *hardwickii*, which is considered vulnerable and listed on the International Union for the Conservation of Nature Red List, is also provided. Information obtained on pinkies (*Nemipterus theodorei* and *N. aurifilum*) is preliminary and includes the first published accounts of the reproductive biology, distribution and growth for *N. theodorei*, which is the main species being retained and marketed. Collectively, the permitted species are valued at $1–2 million annually in Queensland and while the study has made a significant contribution to understanding their biology and improving management, further effort and funding are required to reduce the risk of overfishing these resources.

KEYWORDS: Trawl bycatch, prawns, eastern king prawn, *Penaeus plebejus*, tiger prawns, *Penaeus esculentus*, saucer scallops, *Amusium japonicum balloti*, TEDs, BRDs, square mesh codends, radial escape sections, pipehorses, *Solegnathus hardwickii*, Balmain bugs, *Ibacus chacei, Ibacus brucei, Ibacus alticrenatus*, Moreton Bay bugs, *Thenus orientalis*, stout whiting, *Sillago robusta*, three spot crabs, *Portunus sanguinolentus*, barking crayfish, *Linuparus trigonus*, Mantis shrimps, *Oratosquilla interrupta*, *Oratosquilla stephensoni, Erugosquilla woodmasoni, Harpiosquilla harpax, Nemipterus theodorei*, *Nemipterus aurifilum*, elasmobranchs, rhinobatids, *Aptychotrema rostrata*, urolophids, *Trygonoptera testacea*, *Urolophus* sp., Rajids, *Dipturus polyommata*, Scyliorhinids, *Asymbolus rubiginosus, Galeus boardmani,* generalised linear models, GLM.

3 Background

Prawn trawling generates a higher proportion of discards than any other type of fishing (Alverson et al., 1994). The Queensland East Coast Trawl Fishery (QECTF) is the largest trawl fleet in Australia, and in 2004 consisted of about 500 licensed otter trawlers that were allocated approximately 80,000 boat-nights (predominantly a night-time fishery) of effort annually. In the late 1990s it was estimated that annual production of bycatch by the fishery was likely to exceed 25,000 t (Robins and Courtney, 1998).

The Queensland Government has recognised the need to reduce trawl bycatch and to this end, has undertaken research to address the problem, with FRDC support. Research initiatives include FRDC 93/231.07 (Development of the AusTED), FRDC 96/254 (Commercialisation and Extension of Bycatch Reduction Devices) and FRDC 96/257 (Ecological sustainability of bycatch and biodiversity in prawn trawl fisheries).

The Queensland *Fisheries (East Coast Trawl) Fishery Management Plan 1999* sought to reduce bycatch through the mandatory use of turtle exclusion devices (TEDs) and bycatch reduction devices (BRDs) throughout the entire fishery. (Note: when the project proposal was finalised Moreton Bay trawl fishers were still exempt from using BRDs). Initially, some fishers argued that there were problems with the design, function and safety of TEDs and BRDs in the scallop and deepwater (> 50 fm) sectors and as a consequence, implementation of the devices in these sectors was delayed, but by 2002 both TEDs and BRDs were mandatory in all otter trawl nets throughout the state.

The research undertaken in this project has quantified the effects of TEDs and BRDs in the major prawn trawl sectors. It has also demonstrated the potential bycatch reduction that could be achieved if fishers were to use highly effective BRDs, such as square mesh codends, in certain sectors.

The trawl Management Plan put forward a Review Event to assess and evaluate the process of bycatch reduction. The Review Event was a 40% reduction in bycatch by 1 January 2005. However, it is important to note that demonstrating such a reduction is extremely difficult and dependent upon the ability to measure bycatch production before, and again after, the management changes were introduced. It is both difficult and impractical for fishers to weigh and record their bycatch during normal commercial fishing and as a result, there is no known way to directly measure the total tonnage of bycatch produced in the fishery. Much of the research presented here focused on quantifying the effects of TEDs and BRDs on catch rates, rather than total production.

The trawl fishery Management Plan also increased the number of species that commercial trawler operators were legally allowed to retain and market. In the past the “principal fish” species that operators were permitted to retain was restricted to prawns, scallops, bugs, squid and blue swimmer crabs. However, an additional list of “permitted fish” species has increased the number of species that fishers can retain. This list includes Balmain bugs (*Ibacus* spp.), barking crayfish (*Linuparus trigonus*), cuttlefish (*Sepia* spp.), goatfish (*Upeneus* spp.), mantis shrimp (*Squilla* spp., *Oratosquilla* spp.), octopus (*Octopus* spp.), pinkies (*Nemipterus* spp.) pipefish (*Solegnathus* spp., *Haliichthys* spp., *Halicampus* spp.), three spot crabs (*Portunus sanguinolentus*), sharks (*Carcharhinus* spp.) and whiptails (*Pentapodus paradiseus*). As these species are now permitted catch and the Queensland Government is obliged to manage the stocks, the project also focused on quantifying the population dynamics of many of these species and providing advice on optimising and sustaining their value.

4 Need

There was a strong need to examine how bycatch rates in the Queensland East Coast Trawl Fishery were affected by the mandatory introduction of TEDs and BRDs. This need was driven by a) changes in the *Wildlife Protection Act 1984* and Environment Australia’s Criteria for Assessing Sustainability of Commercial Fisheries, b) national and global political pressure, and c) a general increase in the awareness of prawn trawl bycatch by the Australian public.

Although extremely difficult to quantify, there was also a need to consider the 40% bycatch reduction Review Event outlined in the fishery's Management Plan. Directly measuring the total amount of bycatch produced by prawn trawl fisheries is not possible, and the statistical robustness of estimates is generally considered to be weak (Andrew and Pepperell, 1992). There is therefore a need to improve methods for measuring bycatch if reductions are to be demonstrated.

References

Alverson, D. L., Freeberg, M. H., Murawski, S.A., Pope, J. G., 1994. A global assessment of fisheries bycatch and discards. FAO Fish. Tech. Pap. 339. Rome, FAO. 233 pp.

Andrew, N. L., Pepperell, J. G., 1992. The by-catch of shrimp trawl fisheries. Oceanography and Marine Biology: an Annual Review 30, 527-565.

Robins, J. B.. Courtney, A. J., 1998. Status report on bycatch within the Queensland Trawl Fishery. In: Buxton, C., Eayrs, S. (Eds), Establishing meaningful targets for bycatch reduction in Australian fisheries. Australian Society for Fish Biology Workshop Proceedings, Hobart, 24-25 September 1998, pp. 24-45.

5 Quantifying the effects of bycatch reduction devices in Queensland’s (Australia) shallow water eastern king prawn (*Penaeus plebejus*) trawl fishery

A. J. Courtney, M. L. Tonks, M. J. Campbell, D. P. Roy, S. W. Gaddes and M. F. O’Neill

5.1 ABSTRACT

This study presents results from an experimental 10-day research charter that was designed to quantify the effects of a) a turtle excluder device (TED) and b) a radial escape section bycatch reduction device (BRD) and c) both devices together, on prawn and bycatch catch rates in the Queensland shallow water eastern king prawn (*Penaeus plebejus*) trawl fishery. The bycatch was comprised of 250 taxa, mainly gurnards, whiting, lizardfish, flathead, dragonets, portunid crabs, turretfish and flounders. The observed mean catch rates of bycatch and marketable eastern king prawns from the standard trawl net (i.e., net with no TED or BRD) used during the charter were 11.06 (S.E. 0.90) kg per hectare swept by the trawl gear (ha^{-1}) and 0.94 kg ha^{-1}, respectively. For the range of depths sampled (20.1–90.7 m), bycatch catch rates declined significantly at a rate of 0.14 kg ha^{-1} for every 1 m increase in depth, while prawn catch rates were unaffected. When both the TED and radial escape section BRD were used together they resulted in a 24% reduction in total bycatch catch rate compared to a standard net, but at a 20% reduction in marketable prawn catch rate. The largest reductions were achieved for stout whiting *Sillago robusta* (57% reduction) and yellowtail scad *Trachurus novaezelandiae* (32% reduction). Multidimensional scaling and analysis of similarities revealed that bycatch assemblages differed significantly between depths and latitude, but not between the different combinations of bycatch reduction devices. Despite the lowered prawn catch rates, the reduced bycatch catch rates are promising, particularly for *S. robusta* which is not permitted to be retained by the prawn trawl fleet and yet experiences considerable incidental fishing mortality, and because it is targeted in a separate licensed commercial fishery.

5.2 INTRODUCTION

Prawn trawl fisheries generate a higher proportion of discards than any other fishery type (Alverson et al., 1994) and account for more than one third of the estimated total global discards from fisheries (Pascoe, 1997). In most cases, the weight of the bycatch exceeds that of the prawn catch and is comprised of tens or hundreds of species of fish and invertebrates (Gray et al., 1990; Harris and Poiner, 1990; Watson et al., 1990; Kennelly et al., 1998; Ye et al., 2000; Stobutzki et al., 2001; Steele et al., 2002). Prawn trawl bycatch can also include protected species such as turtles and sea snakes (Wassenberg et al., 1994; Ward, 1996; Milton, 2001). In recent years, increased community awareness of prawn trawl bycatch and scrutiny from conservation agencies have brought pressure upon governments and fishery management agencies in several countries to implement bycatch reduction initiatives (see reviews by Broadhurst, 2000; Hall et al., 2000; Robins et al., 1999), including the mandatory use of bycatch reduction devices (BRDs).

Despite a marked decline in the number of licensed operators over the past two decades, the Queensland prawn trawl fleet has remained Australia's largest, in terms of number of vessels. In 2004 the fishery consisted of approximately 500 licensed otter-board trawlers that were allocated approximately 80,000 boat-nights of fishing effort. An additional 156 smaller beam-trawlers are licensed to trawl in selected rivers and inshore areas. The fishery mainly targets penaeid prawns (*Penaeus* spp. and *Metapenaeus* spp.) and saucer scallops *Amusium ballotti*, but fishers are also permitted to target scyllarid lobsters (*Thenus* spp.) and squid (*Photololigo* spp., *Sepioteuthis* spp. and *Nototodarus* spp.). Issues pertaining to benthic impacts from the fishery and impacts on bycatch species' populations are particularly contentious as about 70% of the otter trawl fishery catch and effort occur in the Great Barrier Reef Marine Park.

Like most prawn trawl fisheries, the total weight of bycatch caught in the Queensland fishery is unknown, but likely to exceed 25,000 t annually (Robins and Courtney, 1998). The weight of the retained catch is approximately 10,000 t annually (Williams, 2002). In recent years, regulations have been introduced progressively that require all otter trawl vessels to have a turtle excluder device (TED) and an additional bycatch reduction device (BRD) installed in every trawl net.

Eayrs et al. (1997) described several BRDs that might be suitable for Australian prawn trawl fisheries. One of these, the radial escape section BRD, was reported to reduce the bycatch of small pelagic finfish in the Queensland fishery, based on an observer program (Robins et al., 2000). The radial escape section BRD (also known as the large-mesh extended-mesh funnel), developed by Watson and Taylor (1988), has been trialled in other prawn trawl fisheries with promising results (Brewer et al., 1998; Garcia-Caudillo et al., 2000; Steele et al., 2002). The objective of the present study therefore, was to quantify the effects of the radial escape section BRD in the shallow water eastern king prawn trawl fishery, which is one of the major sectors of the Queensland East Coast Trawl Fishery and known to have a large component of small pelagic finfish in its bycatch. Specifically, our objectives were to quantify the effects of a) the radial escape section BRD, b) the TED and c) both radial escape section BRD and TED installed together in the net on the catch rates of prawns and bycatch. We also examined the effects of the devices on catch rates and size of individual bycatch species and whether they were likely to alter the bycatch faunal community structure.

5.3 METHODS AND MATERIALS

The effects of the radial escape section BRD and TED were quantified using a dedicated research charter that was conducted over 10 nights in October 2001 and designed to reflect the trawling methods, locations and bycatch of the commercial fishery as much as practically possible. The 17 m commercial trawler, FV *Elizabeth G*, which had a long history in the fishery, was chartered for the work. The vessel towed three nets in triple gear formation (i.e., three nets towed from the port, starboard and stern of the vessel) which is commonly used in the fishery. Measurements from the stern net were not analysed in detail because it fishes differently from the port and starboard nets and because no simultaneous paired comparison was possible with the stern net. New nets were used to minimise variation between the port and starboard nets due to wear and tear, stretching or repairs. Each of the port and starboard nets had a headline length of 12.8 m and a mesh size of 50.8 mm.

5.3.1 Spatial distribution of sampling

Trawling commenced each night about 30 minutes after sunset. Each trawl was towed at 2.3 knots, took approximately 53 minutes and swept precisely two nautical miles along the bottom, measured with a global positioning system (GPS). Trawls were conducted along a straight line to ensure that the nets swept equal areas. After considering the time required to winch away and retrieve nets, process and measure catches on the back deck and “steaming” between trawl locations, it was concluded that about six locations could be trawled each night, resulting in a total of 60 locations and 120 individual trawls (10 nights x six trawls with measures obtained from two of the three nets). To ensure the bycatch composition closely reflected that of the fleet, logbook data were used to determine the spatial distribution of the trawls. The average fishing effort during the months of September-October, inclusive, was calculated for a five-year period (1995–1999) for each of the logbook’s 6 minute x 6 minute spatial grids. The number of trawls allocated to each grid was proportional to the average fishing effort the grid received. Thus, grids that received high levels of fishing effort received more trawls than grids that received low levels of effort.

5.3.2 TED and BRD codend treatments

Four codend types were compared: (1) standard codend only (considered as an experimental “control” net), (2) standard codend with TED only, (3) standard codend with radial escape section BRD only, and (4) standard codend with both TED and radial escape section BRD (Figure 5.3.1). The radial escape section BRD is characterised by a funnel surrounded by large meshes through which bycatch is able to escape. The device trialled in our study had the large escape meshes restricted to its top half (Figure 5.3.1A-C). A hoop constructed from plastic-coated steel wire rope with a diameter of 14 mm was inserted at the aft end of the BRD to ensure that the large meshes were held open and there was adequate space between the funnel and large escape meshes. A second hoop was used at the forward edge of the device, when not used in conjunction with a TED, to ensure the large escape meshes and the funnel were maintained in the correct position. The large meshes were hand-sewn using 6 mm braided polyethylene and equated to 200 mm mesh. The panel of large mesh was 12 meshes wide by 3 meshes deep (Figure 5.3.2).

The standard codend (Figure 5.3.1) was 75 meshes long and 100 meshes in circumference and constructed from 48-ply polyethylene trawl mesh, with a mesh size of 45 mm. The TED used throughout the charter was a modified Wick’s TED (Figure 5.3.1D, E) and constructed from 20 mm solid aluminium bar and was 69 cm wide and 84 cm high, with a bar-space of 12 cm. The grid was sewn into a codend extension that was constructed of the same material used in the standard codend, at 42 degrees from the horizontal, in top-shooter mode (i.e. large bycatch expelled upwards towards the surface). To construct the codend with both the TED and BRD, a radial escape section BRD was sewn to the aft edge of a TED extension to form a single device. The forward hoop of the BRD was removed as the grid of the TED performed the same function.

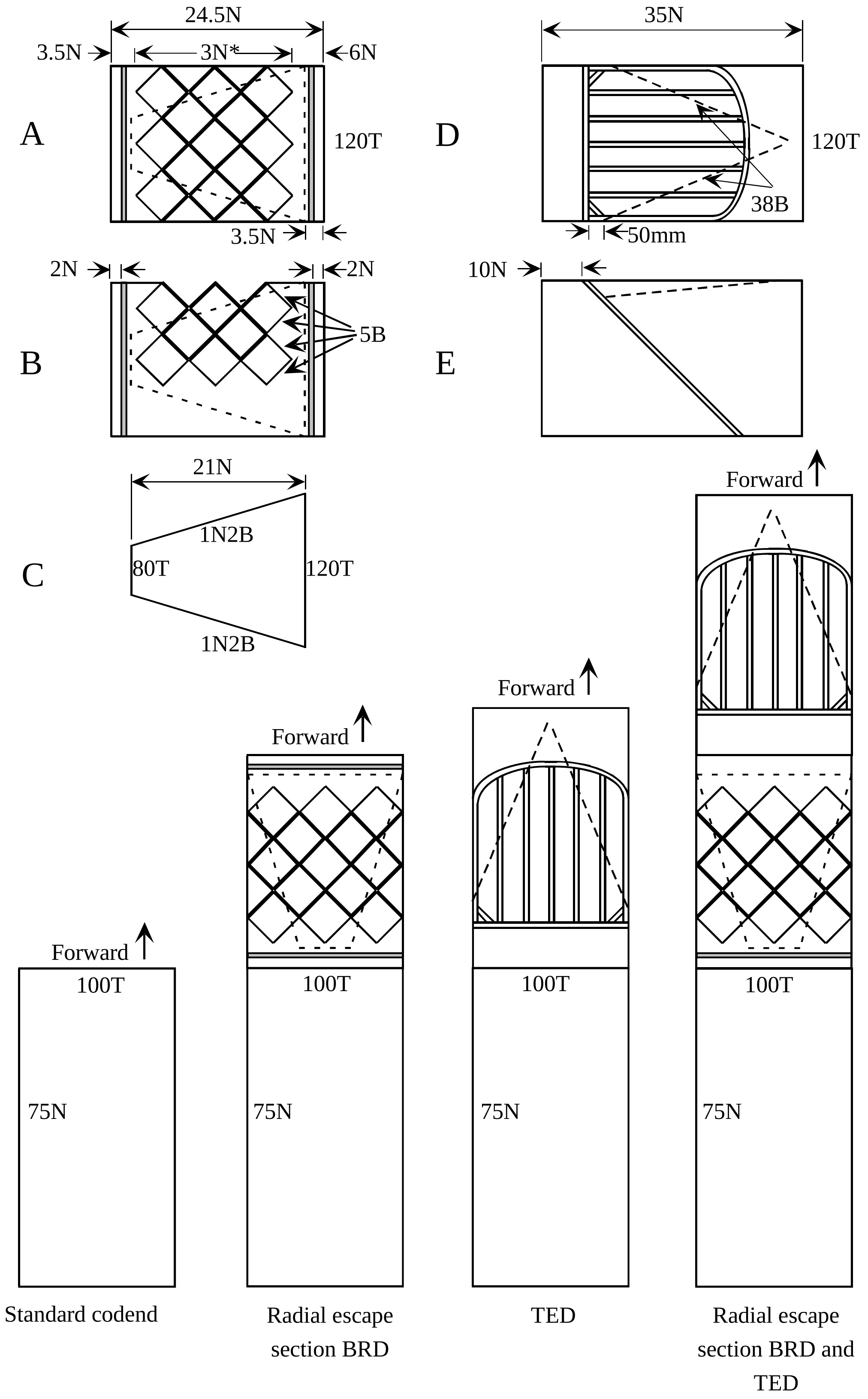


Figure 5.3.1 Design of the radial escape section BRD, TED and the four net treatments used in the charter. A = Plan view of the radial escape section BRD; B = Elevation of the radial escape section BRD; C = Plan or elevation of the funnel used in the radial escape section BRD; D = Plan of the modified Wick's TED; E = Elevation of the modified Wick's TED. Lower diagrams show the four combinations of TED and radial escape section BRD when installed in the nets. Mesh size is 45 mm except for those marked with *, which was hand-sewn and is approximately 200 mm. T and N refer to transverse and normal meshes, respectively.

Figure 5.3.2. The radial escape section BRD and TED after construction. Note the large escape meshes are restricted to the upper half of the codend circumference.

5.3.3 Measuring and sampling the catch

All eastern king prawns *Penaeus plebejus* caught in each of the two nets after each trawl were retained, labelled and frozen for later processing in the laboratory. Byproduct species were removed from each net, weighed and recorded. The bycatch from each net was placed into one or more baskets so that it could be weighed and recorded immediately after each trawl. A sub-sample of the bycatch from each net, weighing approximately 10 kg, was then removed from the basket, labelled, frozen and later sorted to species level in the laboratory. The bycatch in prawn trawl nets is well mixed and sub-sampling in this way can be used to provide unbiased estimates of total numbers and weights of bycatch species (Heales et al., 2000). If the amount of bycatch was small (i.e., less than about 10 kg) then it was retained in its entirety. Large animals weighing more than about 5 kg and species that were protected (collectively referred to as “monsters”) were not included in the sub-sample, but rather identified, weighed, recorded and released.

In the laboratory, the sex and size (mm CL) of every prawn were determined. Prawn lengths were converted to weights using the length-weight relationships reported by Glaister et al. (1990), and individuals larger than 26 mm CL (about 10 g) were regarded as marketable, based on the opinion of the vessel’s commercial skipper. The weight of marketable and non-marketable prawns in each sample was then determined by summation. Each individual in the bycatch sub-samples was identified to species level, counted and the total weight of each species measured and recorded. Length measures for the bycatch species (standard length or total length for fish, carapace length or width for crustaceans, disc width or length for elasmobranchs, total length for echinoderms and shell length for molluscs) were obtained from a maximum of 20 individuals of each species from each sub-sample. The total weight of each sub-sample was determined by summing the individual species weights contained within it.

5.3.4 Calculating catch rates for prawns and bycatch species

All catch rates were converted to weight (kilograms, kg or grams, g) per swept area trawled (hectares, ha). The area swept *S* by net *n* during trawl *t* was estimated thus:

$$S_{tn} = \frac{H \times F \times D}{10{,}000}$$

where H was the headline length of the net (12.8 m), F was the net spread factor (0.75) from Sterling (2005) and D was the distance trawled (2 nautical miles or 3704 m). Division by 10,000 converts the area in square metres to hectares. Because the weight of individual bycatch species was not directly measured (i.e. the bycatch was sub-sampled) it was extrapolated using the following:

$$\hat{W}_{tn}\ ha^{-1} = W_{tn} \times \left(\frac{TBW_{tn}}{SSW_{tn}} \right)$$

where $\hat{W}_{tn}$ is the estimate of the weight of species W caught in net n during trawl t, W_{tn} is the weight of the species W in the sub-sample of trawl t and net n, TBW_{tn} is the total bycatch weight (less monsters) from trawl t and net n, and SSW_{tn} is the weight of the sub-sample of bycatch taken from trawl t and net n.

5.3.5 Statistical design and analysis

Because only two treatments (i.e., two nets) were compared at any one trawl location a randomised incomplete block design was applied (Montgomery, 1997). The four codend types and two net positions (port or starboard) resulted in 12 possible combinations of comparisons (Table 5.3.1). Six trawl locations per night enabled all 12 possible combinations to be repeated every two nights and the order in which they were applied was randomised. After each trawl, the codends were cut off from the net and the next pair of codends sewn on in preparation for the next trawl, as per a pre-determined protocol. The process of removing the codends and sewing on new ones took about 20 minutes between each trawl. The sampling design and treatment protocols ensured that each codend treatment type was sampled in each net position 15 times. It also ensured that if there was a significant difference between the port and starboard nets, referred to as “side-of-boat” effects, then it could be quantified in the analyses and considered in the interpretation of results.

Table 5.3.1. The 12 combinations of codend type and net position applied to the research charter treatment protocol.

Combination of codend type and net position	Port	Starboard
1	Standard codend	Radial escape section BRD
2	Standard codend	TED
3	Standard codend	Radial escape section BRD+TED
4	Radial escape section BRD	Standard codend
5	Radial escape section BRD	TED
6	Radial escape section BRD	Radial escape section BRD+TED
7	TED	Standard codend
8	TED	Radial escape section BRD
9	TED	Radial escape section BRD+TED
10	Radial escape section BRD+TED	Standard codend
11	Radial escape section BRD+TED	Radial escape section BRD
12	Radial escape section BRD+TED	TED

Generalised linear modelling (GLM) using GenStat (2003) statistical software was used to examine the variation in catch rates of bycatch (both total bycatch and individual bycatch species) and prawns. Individual trawl locations (numbered 1–60) were considered as a categorical blocking term. The model distributions and link functions included normal distribution with identity link, binomial distribution with logit link and gamma distribution with logarithm link functions. Three data transformations were trialled when normal distributions were used: power, log and square root. The best model goodness-of-fit was obtained by examining plots of the standardised residuals and if residuals were not normally distributed then the model distribution type or transformation would be changed until normality was attained. The models took the following general form:

$$U = \beta_o + \beta_1(\text{Trawl location}_{1-60}) + \beta_2(\text{Side of vessel}_{1-2}) + \beta_3(\text{Codend type}_{1-4}) + \varepsilon$$

where U was the predicted catch rate for a) total bycatch weight, b) individual bycatch species weight, or c) targeted prawn weight from each trawl, $\boldsymbol{\beta}_o$ and $\boldsymbol{\beta}_2$ were scalar parameters that were estimated, and $\boldsymbol{\beta}_1$ and $\boldsymbol{\beta}_3$ were vector parameters that were estimated and ε was the error term. Only estimates of $\boldsymbol{\beta}_3$ are presented as this parameter quantifies the effects of the different codend types. For purposes of interpretation, the $\boldsymbol{\beta}_3$ parameter estimates were proportionally scaled so that they could be compared against a standard codend parameter value of 1.0. A similar model was used to examine variation in the mean length of bycatch species. However, all length analyses were undertaken using normal distributions with identity link functions. There were no “side-of-boat” effects on length for any species and so this factor was dropped from the model. Again, only results for the $\boldsymbol{\beta}_3$ parameter (i.e., codend effects) are provided.

Multidimensional scaling (MDS) was used to examine variation in the bycatch community structure due to latitude, depth and codend type. The statistical software package PRIMER (Plymouth Routines in Multivariate Ecological Research) by Clarke and Warrick (1994) was used to undertake the analyses. A Bray-Curtis similarity matrix (Bray and Curtis, 1957) was used to examine the similarity between each pair of samples and based on standardised catch rates of individual species in each sample (g ha^{-1}). Two data transformations were used, square-root and presence-absence, but only results from analyses that produced the lowest stress levels [stress values ≤ 0.2 are considered to provide adequate representation (Clarke and Warrick, 1994)] are presented. The PRIMER routine ANOSIM (analysis of similarities) is a simple non-parametric permutation applied to the similarity matrix to test for differences between groups. ANOSIM calculates an *R*-statistic which is usually between 0 and 1, such that 0 represents low dissimilarity between groups, and 1 represents high dissimilarity. A global *R*-statistic refers to the difference between all groups. A second routine SIMPER (similarity percentages) was used to examine the contribution of species to the average dissimilarity between groups. To reduce the number of factor levels, depths were rounded to the nearest 10 m and latitude to the nearest 0.5 degree. MDS was carried out on species that were present in at least 5% of samples to avoid the species-sample matrix table from being dominated by zeros.

5.4 RESULTS

The results were limited to the targeted prawn catch and bycatch. Results for byproduct are not presented, due to the variability in the size at which some byproduct species (i.e., cuttlefish, octopus) are retained and marketed by commercial fishers.

5.4.1 Catch rates and effects of bycatch reduction devices

The charter produced 120 measures of bycatch and eastern king prawn catch rates and bycatch sub-samples from 60 locations (Figure 5.4.1) (i.e., 60 locations with measurements and sub-samples obtained from two nets towed simultaneously at each location). Overall mean catch rates from all net types were 9.56 (S.E. 0.44) kg ha^{-1} for bycatch and 0.98 (S.E. 0.09) kg ha^{-1} for prawns. The depth of the trawls ranged between 20.1 m and 90.7 m, with most between 40.0–90.0 m. There was no significant effect of depth on prawn catch rates, however bycatch catch rates declined significantly at a rate of 0.14 kg ha^{-1} for every one metre increase in depth (Figure 5.4.2).

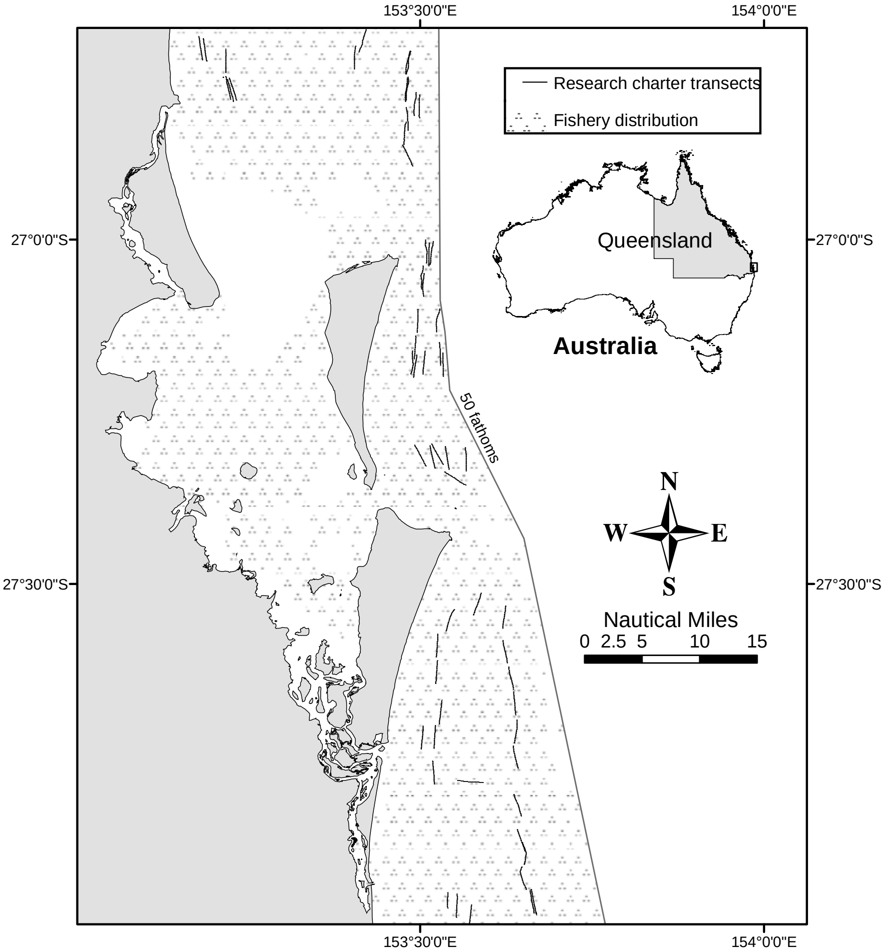


Figure 5.4.1. Location of the 60 two-nautical mile trawl sites in the shallow water eastern king prawn fishery that were sampled during the experimental research charter. Measures of prawn catches, bycatch and bycatch sub-samples were obtained from two nets (port and starboard) towed simultaneously at each location. Each "transect" is comprised of approximately 50 location data point readings taken directly from the vessel's global positioning system at one-minute intervals while trawling and imported into a geographic information mapping program (ArcVIEW) for presentation.

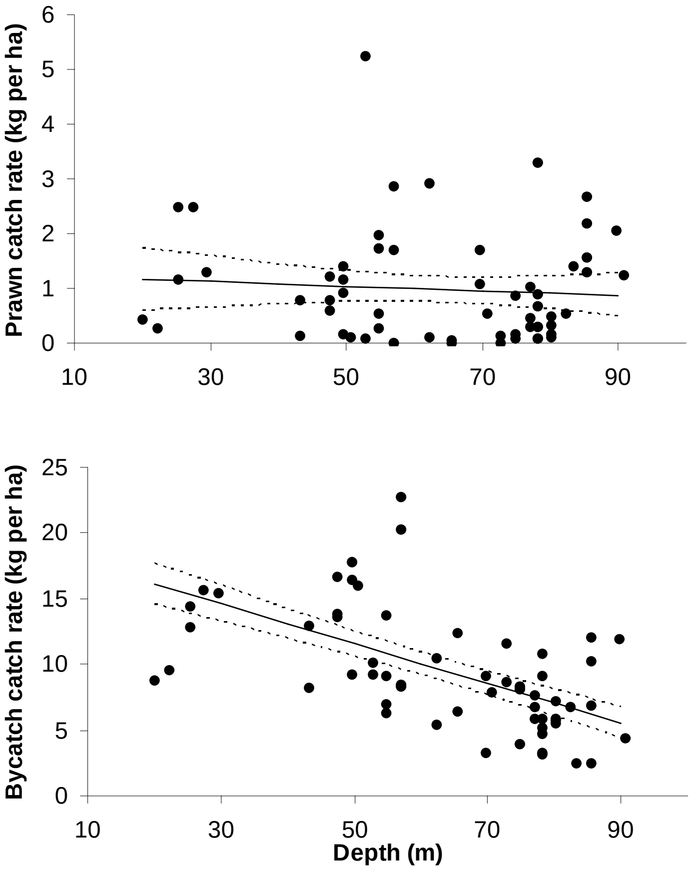


Figure 5.4.2. The effect of depth on catch rates of prawns and bycatch in the Queensland shallow water eastern king prawn trawl fishery, based on measurements from the experimental research charter. Dotted lines are 95% confidence intervals of the mean.

The observed mean catch rate of bycatch from the standard net was 11.06 (S.E. 0.90) kg ha^{-1} (Table 5.4.1). All codend treatment types significantly ($P < 0.05$) reduced bycatch catch rates compared to the standard net, and all four treatments differed significantly from each other. The net with both the radial escape section BRD and TED resulted in the largest reduction of 24% ($\boldsymbol{\beta}_3$ parameter estimate of 0.76, Table 5.4.1), while the radial escape section by itself resulted in a reduction of 19% ($\boldsymbol{\beta}_3$ parameter estimate of 0.81) and the TED by itself a reduction of 10% ($\boldsymbol{\beta}_3$ parameter estimate of 0.90).

Over the 10 days a total of 18,289 prawns from 14 species were caught. Eastern king prawns (*P. plebejus*) made up 80% of the catch numerically. The second most numerous species was the hardback prawn or southern rough prawn (*Trachypenaeus curvirostris*), which comprised about 15%. Other species present in relatively small numbers included the red endeavour prawn (*Metapenaeus ensis)*, the blue-legged king prawn (*Penaeus latisulcatus*), the red-spot king prawn (*Penaeus longistylus*) and the brown tiger prawn (*Penaeus esculentus*). About half of the prawn species had no commercial market value and most were relatively uncommon in the catch. The observed mean catch rate of marketable eastern king prawns (i.e., those larger than 10 g) from the standard net was 0.94 kg ha^{-1} (Table 5.4.1). There was a significant reduction of 20% ($P < 0.05$, $\boldsymbol{\beta}_3$ parameter estimate of 0.80, Table 5.4.1) in the net with both radial escape section BRD and TED. Most of the prawn loss was attributed to the TED ($P < 0.05$, $\boldsymbol{\beta}_3$ parameter estimate of 0.88), while the reduction in the net with the BRD only was not significant. There were no significant effects on the catch rates of non-marketable prawns (i.e. those smaller than 10 g), which had an observed mean catch rate of 0.05 kg ha^{-1}.

A total of 250 taxa were recorded in the 120 bycatch sub-samples, with most species being relatively uncommon. For example, 178 taxa (71% of species) occurred in fewer than 10% of sub-samples and 68 taxa (27% of species) were found in only one sub-sample. The 10 species with the highest mean catch rates were the gurnard *Lepidotrigla argus* (2126.23 g ha^{-1}), stout whiting *Sillago robusta* (780.81 g ha^{-1}), lizardfish *Saurida grandisquamis* (721.55 g ha^{-1}), flathead *Platycephalus longispinis* (435.60 g ha^{-1}), dragonet *Callionymus calcaratus* (379.74 g ha^{-1}), dragonet *Callionymus limiceps* (214.25 g ha^{-1}), portunid crab *Portunus rubromarginatus* (173.08 g ha^{-1}), the turretfish *Tetrosomus concatenates* (169.29 g ha^{-1}), the spot-tail wide-eye flounder *Engyprosopon grandisquama* (167.94 g ha^{-1}) and the slender flounder *Pseudorhombus tenuirastrum* (152.9 g ha^{-1}).

A complete list of 406 species that the project recorded in the shallow water eastern king prawn bycatch, and their catch rates, is provided in Appendix 1. This list includes the 250 species recorded from the charter and additional species recorded in bycatch obtained from opportunistically sampling on board commercial vessels operating in this sector.

Table 5.4.1. The effects of the radial escape section BRD and TED on the catch rates of bycatch and target prawn species *Penaeus plebejus* based on 120 individual net tows (60 trawls x 2 nets). Generalised linear modelling was used to quantify codend treatment effects. Significant differences between treatments ($P < 0.05$) are bolded and identified by different alphabetic characters (A, B, C or D). Parameter estimates were proportionally scaled so they can be compared to a standard net parameter value of 1. Standard errors in parentheses.

Response variable	**Mean observed catch rate in kg ha^{-1} Standard net**	**Predicted change in catch rates based on generalised linear model parameter estimates (proportionally scaled to a Standard net parameter value of 1)**			**Distribution type**
		TED only	**Radial escape section BRD only**	**Radial escape section BRD and TED together**	
Total bycatch	**11.06 (0.90) A**	**0.90 (0.03) B**	**0.81 (0.03) C**	**0.76 (0.03) D**	**Gamma**
Marketable prawns	**0.94 (0.16) A**	**0.88 (0.02) BC**	**0.91 (0.02) AC**	**0.80 (0.02) B**	**Normal (square-root transformed)**
Non-marketable prawns	0.05 (0.03) A	1.25 (0.28) A	1.14 (0.25) A	1.25 (0.28) A	Normal (log transformed)

The codend effects were examined for 26 species that comprised 90% of the total bycatch weight from the standard net (Table 5.4.2). Conclusive analyses for the remaining species were hindered due to their low occurrence (i.e. they were present in fewer than 8% of sub-samples). The gurnard *L. argus* was the most commonly encountered species and occurred in 91% of sub-samples, followed by the portunid crab *Portunus rubromarginatus* (90% of samples), the lizardfish *Saurida grandisquamis* (83% of samples) and the triangular boxfish *Tetrosomus concatenates* (76% of samples). Catch rates for *L. argus* (2698.03 g ha^{-1}) were more than twice that of any other species. Of the 26 species, 20 displayed lower predicted mean catch rates, or probabilities of capture, from the net that had both the BRD and TED, however significant reductions (P <0.05) were only detected for three species: *L. argus*, *S. robusta* and the scad *Trachurus novaezelandiae*. In general, the net with both the BRD and TED resulted in the largest reductions, followed by the net with the BRD only, and then by the net with the TED only (Table 5.4.2). The largest reduction was achieved for *S. robusta* where catch rates fell 57% from 1275.12 g ha^{-1} in the standard net to a predicted rate of 548.30 g ha^{-1} in the net with both the BRD and TED. Predicted reductions for *L. argus* and *T. novaezelandiae* in the net with both devices were 28% and 32%, respectively, compared to the standard net (Table 5.4.2).

The effects on the mean length of bycatch species were variable. Seventeen of the 26 species examined above were unaffected, while the mean lengths of nine species were significantly affected by one or both devices (Table 5.4.3). The flathead *Ratabulus diversidens* had the largest change in length – a reduction from 195.10 mm in the standard net to 160.24 mm in the net with both devices. The results suggest that larger individuals escaped through both the TED and BRD, thus lowering the mean size of those retained. The scorpinid *Maxillicosta whitleyi* was the smallest fish species with a significant effect. Mean length declined from 44.76 mm in the standard net to 43.45 mm in the net with both the TED and BRD. Not all significant changes were reductions. For example, the mean length of the lizardfish *S. grandisquamis* and stout whiting *S. robusta* increased in nets with a TED, suggesting that proportionally more small individuals of these species escaped via the TED. The mean length of goatfish *Upenaeus asymmetricus* also increased, but mainly due to the BRD.

Table 5.4.2. Catch rates of the more frequently encountered bycatch species caught during the research charter and the effects of the radial escape section BRD and TED on their catch rates. Generalised linear modelling was used to quantify effects. Significant effects ($P < 0.05$) are bolded. Treatments with the same alphabetic character (A, B, C or D) were not significantly different. Distribution types used in the models were N = normal, G = gamma and B = binomial. The parameter estimates have been proportionally scaled so they can be compared to a Standard net parameter value of 1. Standard errors (S.E.) in parentheses.

Species	Occurrence (%) in 120 samples (60 trawls x 2 nets)	Standard net mean observed catch rate (g ha^{-1})	Standard net predicted probability of capture	Predicted change in catch rates based on generalised linear model parameter estimates (proportionally scaled to a Standard net parameter value of 1)			Distribution type
				TED only	Radial escape section BRD only	Radial escape section BRD and TED together	
Lepidotrigla argus	**91**	**2698.03 (287.00) A**	*****	**0.82 (0.001) B**	**0.81 (0.06) B**	**0.72 (0.05) B**	**N (log)**
Portunus rubromarginatus	90	206.04 (41.93)	*	1.14 (0.18)	1.17 (0.18)	1.03 (0.16)	G
Saurida grandisquamis	83	670.86 (150.42)	*	1.52 (0.26)	0.90 (0.15)	0.98 (0.15)	G
Tetrosomus concatenates	76	64.64 (15.80)	*	1.20 (0.30)	1.20 (0.30)	1.25 (0.33)	G
Pseudorhombus tenuirastrum	73	121.68 (24.95)	*	0.96 (0.19)	1.25 (0.24)	1.11 (0.22)	G
Platycephalus longispinis	72	573.78 (121.30)	*	1.15 (0.24)	1.42 (0.30)	0.88 (0.19)	N (log)
Optivus sp. *1*	70	91.36 (24.76)	*	0.98 (0.12)	0.89 (0.11)	1.10 (0.14)	G
Trachinocephalus myops	68	177.97 (41.75)	*	0.72 (0.19)	0.92 (0.23)	0.81 (0.21)	G
Portunus argentatus	65	113.88 (56.74)	*	0.89 (0.19)	0.99 (0.21)	0.98 (0.21)	G
Engyprosopon grandisquama	61	242.03 (70.04)	*	0.84 (0.15)	0.95 (0.17)	0.91 (0.16)	N (log)
Callionymus calcaratus	60	525.81 (174.108)	*	0.94 (0.12)	0.96 (0.12)	0.80 (0.09)	G
Maxillicosta whitleyi	60	99.90 (39.91)	*	0.84 (0.18)	0.91 (0.19)	1.16 (0.22)	G
Inegocia japonica	57	141.51 (50.03)	*	1.41 (0.36)	1.34 (0.32)	1.16 (0.27)	G
Aptychotrema rostrata	55	N/A	0.56 (0.08)	0.61 (0.07	0.56 (0.09)	0.48 (0.06)	B
Torquigener altipinnis	51	100.79 (32.45)	*	0.70 (0.17)	1.09 (0.27)	0.84 (0.19)	G
Callionymus limiceps	49	254.65 (100.99)	*	1.22 (0.24)	0.92 (0.15)	0.78 (0.12)	G
Sillago robusta	**38**	**1275.12 (395.81) A**	*****	**0.74 (0.16) B**	**0.56 (0.12) C**	**0.43 (0.09) C**	G
Gnathophis grahamii	36	N/A	0.32 (0.07)	0.37 (0.05)	0.42 (0.04)	0.27 (0.04)	B
Platycephalus caeruleopunctatus	36	N/A	0.40 (0.05)	0.36 (0.05)	0.36 (0.07)	0.30 (0.06)	B
Ratabulus diversidens	29	63.59 (22.01)	*	0.68 (0.42)	0.62 (0.41)	0.49 (0.36)	G
Pseudorhombus arsius	18	70.95 (28.19)	*	0.90 (0.57)	0.89 (0.38)	0.72 (0.33)	G
Trachurus novaezelandiae	**18**	**316.03 (154.88) A**	*****	**0.86 (0.17) AB**	**0.80 (0.10) AB**	**0.68 (0.09) B**	**N (log)**
Upeneus asymmetricus	18	115.72 (61.60)	*	1.17 (0.34)	0.77 (0.26)	0.73 (0.21)	G
Paraplagusia unicolour	14	196.69 (120.20)	*	0.76 (0.37)	0.61 (0.29)	0.84 (0.39)	G
Dasyatis kuhlii	8	N/A	0.30 (17.03)	0.14 (22.13)	0.06 (1.65)	0.05 (1.97)	B
Plotosus lineatus	8	299.66 (297.19)	*	0.67 (0.17)	0.58 (0.15)	0.75 (0.19)	N (log)

Table 5.4.3. Effects of the TED and radial escape section BRD on bycatch species' lengths (in mm). Significant effects ($P < 0.05$) are bolded. Lengths were normally distributed. Treatments with the same alphabetic character (A, B, C or D) were not significantly different. Standard errors in parentheses.

		Generalised linear model estimates of mean lengths			
Species	**Number of individuals measured**	**Standard net**	**TED only**	**Radial escape section BRD only**	**Radial escape section BRD and TED together**
Lepidotrigla argus	2152	**88.25 (0.59) A**	**86.50 (0.59) B**	**88.03 (0.59) AB**	**89.13 (0.59) A**
Portunus rubromarginatus	1110	43.98 (0.51)	44.77 (0.55)	43.97 (0.52)	44.33 (0.50)
Saurida grandisquamis	744	**234.59 (4.29) A**	**253.04 (4.68) B**	**239.72 (3.96) A**	**241.55 (3.51) AB**
Tetrosomus concatenatus	579	69.51 (2.29)	72.01 (1.97)	69.01 (2.19)	74.51 (1.92)
Pseudorhombus tenuirastrum	465	**191.89 (3.52) AB**	**193.16 (2.58) AB**	**198.39 (2.43) A**	**191.02 (2.46) B**
Platycephalus longispinis	1193	**141.67 (0.93) AB**	**139.05 (1.08) A**	**142.49 (1.01) B**	**141.76 (0.90) AB**
Optivus sp. *1*	1019	79.18 (0.49)	79.48 (0.44)	80.35 (0.39)	79.33 (0.43)
Trachinocephalus myops	496	136.03 (3.10)	130.87 (3.65)	136.37 (2.88)	131.88 (3.14)
Portunus argentatus	1029	32.03 (0.30)	31.31 (0.24)	31.51 (0.29)	31.51 (0.27)
Engyprosopon grandisquama	1144	89.65 (0.76)	88.71 (0.92)	88.51 (0.80)	89.93 (0.83)
Callionymus calcaratus	919	**120.28 (0.72) AB**	**118.17 (0.83) A**	**121.22 (0.77) B**	**122.32 (0.74) B**
Maxillicosta whitleyi	873	**44.76 (0.46) A**	**43.80 (0.49) AC**	**46.03 (0.45) B**	**43.45 (0.42) C**
Inegocia japonica	509	111.14 (2.65)	116.63 (3.07)	109.80 (2.69)	111.95 (2.49)
Aptychotrema rostrata	158	482.20 (17.80)	430.60 (26.00)	432.20 (12.70)	466.20 (21.20)
Torquigener altipinnis	448	85.35 (1.29)	85.91 (1.29)	83.31 (1.11)	83.46 (0.95)
Callionymus limiceps	666	117.79 (1.74)	117.27 (1.88)	116.46 (1.43)	116.73 (1.68)
Sillago robusta	655	**135.50 (1.08) A**	**139.14 (1.32) BC**	**136.13 (1.35) AB**	**140.88 (88) C**
Gnathophis grahamii	101	289.66 (7.76)	294.10 (9.05)	290.86 (17.08)	299.55 (10.36)
Platycephalus caeruleopunctatus	82	277.74 (10.25)	277.13 (9.57)	267.69 (9.07)	278.17 (9.19)
Ratabulus diversidens	161	**195.10 (10.09) A**	**172.68 (8.41) AB**	**175.43 (9.09) AB**	**160.24 (8.38) B**
Pseudorhombus arsius	41	214.10 (13.30)	231.60 (28.10)	220.80 (19.30)	222.50 (16.40)
Trachurus novaezelandiae	175	142.57 (0.84)	144.92 (1.39)	149.44 (3.47)	143.30 (1.81)
Upeneus asymmetricus	226	**99.93 (1.05) A**	**105.91 (1.28) B**	**100.05 (1.07) A**	**101.06 (1.25) A**
Paraplagusia unicolour	230	198.71 (2.27)	199.19 (2.40)	202.78 (2.19)	199.31 (2.09)
Dasyatis kuhlii	12	284.60 (43.80)	-	219.60 (80.10)	-
Plotosus lineatus	36	172.96 (3.76)	172.96 (3.76)	159.63 (22.98)	164.63 (9.92)

5.4.2 Variation in bycatch assemblages

Variation in bycatch community structure and the effects of the TED and BRD multidimensional scaling (MDS) was carried out using all 120 sub-samples and the catch rates of 118 species that were present in 5% or more of the sub-samples. The resulting stress value was 0.16 for a two-dimensional ordination (Figure 5.4.3A-C). Analysis of similarities (ANOSIM procedure in PRIMER) revealed that bycatch assemblages differed significantly between depths (global $R = 0.563$, $P < 0.001$), with the largest differences between the shallowest and deepest categories. Pairwise tests for the a) 20 m and 70 m groups, b) 20 m and 80 m groups, c) 20 m and 90 m groups, and d) 30 m and 90 m groups all produced *R*-statistic values of 1.000. Species that accounted for high proportions of the dissimilarity between the shallowest (20 m) and deepest (90 m) sites were *S. robusta* (11.39%), *L. argus* (9.30%), lemon tonguesole *P. unicolour* (5.59%), *C. limiceps* (5.19%), the toadfish *T. altipinnis* (4.80%), the painted lizardfish *T. myops* (3.92%), the flatfish *Arnoglossus fisoni* (3.86%), the goatfish *U. asymmetricus* (2.91%) and the Japanese flathead *I. japonica* (2.68%). *L. argus* was completely absent from the 20 m sites while *S. robusta, P. unicolour, T. altipinnis, A. fisoni* and *U. asymmetricus* were absent from the 90 m sites.

Bycatch assemblages were also affected, to a lesser degree, by latitude (global $R = 0.150$, $P < 0.001$), with the largest difference between the northernmost (26.5^{o}S) and southernmost (28^{o}S) sites (*R*-statistic = 0.734, Figure 5.4.3B). Species that accounted for high proportions of the dissimilarity between these sites were *L. argus* (7.74%), *S. robusta* (6.02%), *P. longispinis* (4.01%), *S. grandisquamis* (3.72%), the spiny flounder *Pseudorhombus tenuirastrum* (3.23%) and *P. unicolour* (2.98%). Catch rates of *S. robusta* and *P. unicolour* were about 10 times higher at the northernmost sites.

Given the marked influence of depth, a two-way crossed analysis of similarities was undertaken to examine the effects of the codend types with depth as the first factor and codend type as the second. The depth effect was confirmed (global *R*-statistic = 0.561, $P < 0.001$) but there was no significant effect of codend type on bycatch assemblages (global $R = –0.033$), nor was there any evidence of clustering or grouping of species from the MDS due to codend type (Figure 5.4.3C).

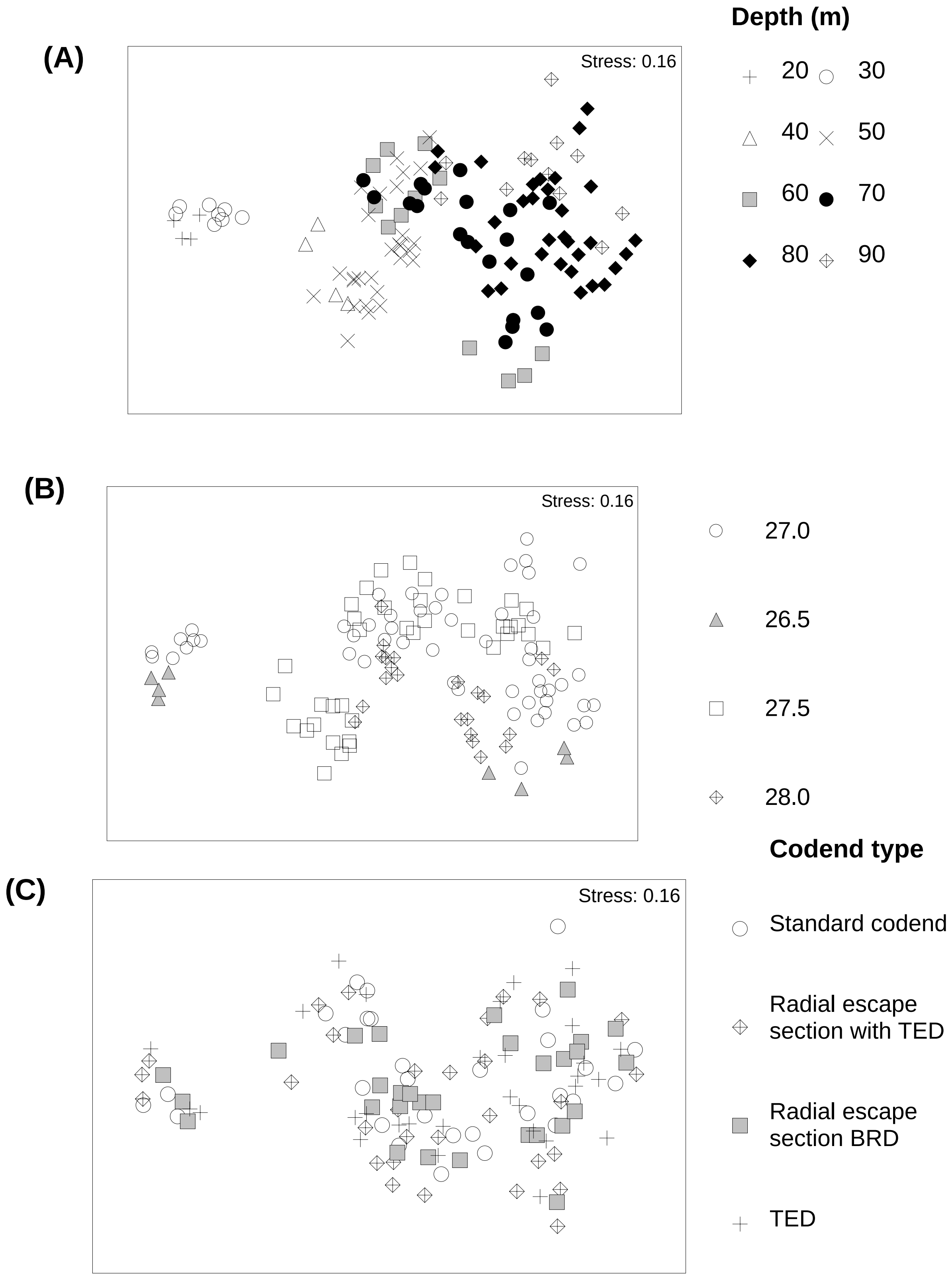


Figure 5.4.3. Two-dimensional MDS of bycatch sub-samples from an experimental research charter undertaken in the Queensland shallow water eastern king prawn trawl fishery. Catch rates were square-root transformed. The analyses used all 120 sub-samples and 118 species. Factors examined were (A) depth, (B) latitude and (C) codend type.

5.5 DISCUSSION

5.5.1 Evaluating the performance of the TED and radial escape section BRD

Our study has shown that bycatch can be significantly reduced ($\boldsymbol{\beta}_3$ parameter estimate of 0.76 equates to a 24% reduction) in the shallow water eastern king prawn fishery by using both the TED and radial escape section BRD together, but at a significant loss of marketable prawn catch ($\boldsymbol{\beta}_3$ parameter estimate of 0.80 equates to a 20% reduction). Brewer et al. (1998) undertook a scientific trial at sea comparing several TEDs and BRDs in Australia's Northern Prawn Fishery. They found that the radial escape section BRD reduced bycatch of small finfish by an average of 20–40% compared to a standard net with no TED or BRD, but also recorded a significant prawn loss of about 20% during one of the two legs of the trial. Garcia-Caudillo et al. (2000) compared a radial escape section BRD with TED against a net with TED-only (i.e., control net) during two research cruises in the Gulf of California shrimp (= prawn) fishery. Total bycatch was reduced by 40.2% during the first cruise and 43.0% during the second. They also recorded prawn losses of 7.3% and 5% in the first and second cruises respectively, due to the radial escape section BRD. Steele et al. (2002) evaluated the effects of an extended mesh funnel BRD (= radial escape section BRD) with TED against a net with TED-only (i.e., control net) in the Florida shrimp fishery. They found that, for a range of different net sizes, the radial escape section reduced the total weight of fish bycatch by 18–60%. Four of their six experimental trials resulted in a reduction in prawn catch that varied between 5% and 29%, compared to the control net. Collectively, when results from Brewer et al. (1998), Steele et al. (2002), Garcia-Caudillo et al. (2000) and our study are considered together they all indicate that the radial escape section is a highly effective BRD but likely to incur some loss of prawn catch.

Catch rates for the most commonly encountered species, the gurnard *L. argus*, were reduced by 28% and attributed to roughly equal numbers escaping through the TED opening and the radial escape section (Table 5.4.2). However the largest reductions, which were achieved for the stout whiting *S. robusta* (57% reduction) and the scad *T. novazelandiae* (32% reduction), were attributed mainly to the radial escape section. Both of these species are bentho-pelagic with fusiform body shape and a reasonably strong swimming ability. Length analyses (Table 5.4.3) suggested that it was mainly the smaller stout whiting that escaped, while there was no significant effect on the size of the scad. The devices had no effect on the catch rates or size of portunid crabs, *P. rubromarginatus* and *P. argentatus.* The results suggest that the radial escape section is more effective at reducing the capture of species with strong directional swimming ability and a body form that allows unhindered passage through the large meshes. It is possible that larger reductions could be achieved by moving the device further toward the codend draw string, thus shortening the distance that species are required to swim to escape. Broadhurst et al. (2002) demonstrated that bycatch exclusion increased as a square mesh panel BRD was positioned further down the net, but at significant loss of prawn catch. In the present study, the large escape meshes were restricted to the upper-half of the radial escape section BRD (Figure 5.3.1B). It is possible that larger reductions could be achieved by extending the large meshes around the entire circumference of the net, thus extending the area through which bycatch could escape, but this would likely result in larger prawn losses.

There were no consistent patterns in mean length due to the effects of the TED, the radial escape section BRD, or when both devices were used together (Table 5.4.3). Most species experienced no significant effects of the devices on size and when significant effects were detected, about half were increases in length, and half decreases. This is consistent with the effects on length found by Garcia-Caudillo (2000) while testing a radial escape section BRD in the Gulf of Mexico.

Despite the reduced prawn catch rate, results for stout whiting *S. robusta* are particularly encouraging because there is a separate licensed commercial fishery for this species in Queensland that spatially overlaps with the prawn fishery. Prawn trawl fishers are not permitted to retain stout whiting and yet the estimated incidental catch and mortality imposed by the prawn fleet is likely to exceed the total allowable catch for the stout whiting fishery, which is currently 1100 t. The 57% reduction achieved for *S. robusta* indicates that there is great potential to reduce the incidental fishing mortality on this species.

5.5.2 Variation in bycatch composition

The bycatch was characterised by a) a large number of fish and invertebrate species (250 taxa), most of which were uncommon (71% occurred in fewer than 10% of sub-samples), b) dominant species (by weight) were a mixture of benthic and demersal finfish and crabs, mainly gurnards, stout whiting, portunid crabs, lizardfish, flatheads, dragonets and flounders c) faunal community assemblages that were affected by depth (20–90 m) and latitude (25^{o}–28^{o} S). When results from the single species (Table 5.4.2) and multivariate (Figure 5.4.3) analyses were considered, they indicated that the TED and radial escape section reduced catch rates for most bycatch species but not enough to significantly alter the general composition of the bycatch or to result in distinct “non-BRD” and “BRD” groups.

Watson et al. (1990) described the temporal and spatial variation in bycatch fauna from a prawn trawl fishery in Central Queensland (18^{o}–19^{o} S). They sampled eight sites on a monthly basis for two years and recorded 477 taxa. The faunal composition was more affected by site location than by sampling time, and characterised by three spatial groups across the continental shelf 1) nearshore, 2) midshelf, and 3) inter-reef. Stobutzki et al. (2001) recorded 359 teleost and elasmobranch species from 401 trawl samples from the Australian Northern Prawn Fishery (10^{o}–15^{o} S). They also concluded that variation in the bycatch was higher due to regional, rather than seasonal differences. Kennelly et al. (1998) also found highly significant effects due to location in the New South Wales eastern king prawn trawl bycatch (29^{o}–33^{o} S), but no significant effects due to season or year. These studies and the present study results confirm strong spatial differences in prawn trawl bycatch composition within each fishery. In the present study, depth had a stronger influence on bycatch composition than latitude or codend type.

5.5.3 Total annual bycatch production and the effects of bycatch reduction devices

TEDs and BRDs were introduced progressively in the Queensland East Coast Trawl Fishery from November 1999 to July 2001 and are now compulsory throughout the fishery, including the shallow water eastern king prawn fishery. The catch rates from the standard nets used during the charter can be used to estimate the amount of bycatch produced prior to the management changes. For example, the mean standard net catch rate was 11.06 (S.E. 0.90) kg ha^{-1} for bycatch and 0.94 (S.E. 0.16) kg ha^{-1} for prawns, or 11.78 (S.E. 2.19) kg bycatch per kg of prawns. Logbook data show that the average annual reported harvest from the shallow water (< 50 fm) eastern king prawn fishery from 1988–1999 inclusive was about 929.6 (S.E. 39.5) t, which using simple extrapolation, equates to an average annual bycatch of 10,948.8 (S.E. 2085.2) t. If trawler operators adopted the TED and radial escape section BRD and the 24% reduction in bycatch (Table 5.4.1) was extrapolated to the fleet, it would equate to an annual reduction of about 1824 t, but at a considerable loss (20%) of marketable prawns. Garcia-Caudillo et al. (2000) extrapolated the 40.2% reduction in bycatch attained during their research cruise to the total fleet operating in the Gulf of California fishery and concluded that bycatch could be reduced by 73,000 t annually. Kennelly et al. (1998) described the bycatch from the New South Wales ocean prawn trawl fishery, which also targets eastern king prawns. They estimated that over a two-year period from winter 1990 to autumn 1992 approximately 1578 t of prawns were caught with an associated 16,435 t of bycatch, of which they estimated 2953 t was retained for sale (as byproduct). These estimates equate to prawn-to-total bycatch ratios of 10.4:1 and prawn-to-discarded bycatch (with byproduct retained) of 8.5:1, which is slightly lower than we obtained.

Other changes were introduced in the fishery’s Management Plan with the introduction of TEDs and BRDs that may have also indirectly affected bycatch production, including a licence buy-back scheme, the allocation of annual fishing-nights to individual licensees and an effort trading scheme that prevents overall increases in fleet fishing power (also known as effort creep). Collectively, these measures have lead to an overall reduction in trawl fishing effort for the entire fishery, and shifts in the temporal and spatial distribution of thousands of boat-days of effort within and between the trawl sectors. Logbook data indicate that effort in the shallow water eastern king prawn sector has declined from an annual average of about 18,500 boat-days in the period 1988–1999 to about 14,900 boat-days in the period 2000–2003 after the Plan was implemented – a reduction of approximately 20%. As a result, bycatch is likely to have declined in this sector since the introduction of the Plan due to reduced effort, in addition to reductions due to the introduction of TEDs and BRDs.

5.6 CONCLUSION

The main finding from the study was that when used together, the TED and radial escape section BRD reduced total bycatch catch rates by 24%, but at a 20% reduction in the marketable prawn catch rate, compared to a standard net with no TED or BRD (Table 5.4.1). The composition of the bycatch varied with depth and latitude, and although the devices reduced the catch rates for most species, they are unlikely to alter the general character of the bycatch composition. While the bycatch reductions are promising, the reduced prawn catch will almost certainly dissuade fishers from voluntarily adopting this combination of devices. The radial escape section BRD was most effective at reducing bentho-pelagic species with fusiform body shape and good swimming ability and showed great potential for reducing the incidental fishing mortality of stout whiting *S. robusta* which is targeted in another fishery.

5.7 REFERENCES

Alverson, D.L., Freeberg, M.H., Pope, J.G., Murawski, S.A., 1994. A global assessment of fisheries bycatch and discards. FAO Fish. Tech. Pap. 330, 233pp.

Bray, J.R., Curtis, J.T., 1957. An ordination of the upland forest communities of Southern Wisconsin. Ecol. Monogr. 27, 325-349.

Brewer, D., Rawlinson, N., Eayrs, S., Burridge, C.Y., 1998. An assessment of bycatch reduction devices in a tropical Australian prawn trawl fishery. Fish. Res. 36, 195-215.

Broadhurst, M.K., 2000. Modifications to reduce bycatch in prawn trawls: a review and framework for development. Rev. Fish Biol. Fish. 10, 27-60.

Broadhurst, M.K., Kennelly, S.J., Gray, C.A., 2002. Optimal positioning and design of behavioural-type by-catch reduction devices involving square-mesh panels in penaeid prawn-trawl codends. Mar. Freshw. Res. 53, 813-823.

Clarke, K.R., Warrick, R.M., 1994. Change in marine communities: an approach to statistical analysis and interpretation. Plymouth Marine Laboratories, Plymouth.

Eayrs, S., Buxton, C., McDonald, B., 1997. A guide to bycatch reduction in Australian prawn trawl fisheries. Australian Maritime College.

Garcia-Caudillo, J.M., Cisneros-Mata, M.A., Balmori-Ramirez, A., 2000. Performance of a bycatch reduction device in the shrimp fishery of the Gulf of California, Mexico. Biol. Conserv. 92, 199-205.

GenStat, 2003. GenStat, 7th ed.. Lawes Agricultural Trust.

Glaister, J.P., Montgomery, S.S., McDonall, V.C., 1990. Yield-per-recruit analysis of eastern king prawns, *Penaeus plebejus* Hess, in eastern Australia. Aust. J. Mar. Freshw. Res. 41, 175-197.

Gray, C.A., McDonall, V.C., Reid, D.D., 1990. By-catch from prawn trawling in the Hawkesbury River, New South Wales: species composition, distribution and abundance. Aust. J. Mar. Freshw. Res. 41, 13-26.

Hall, M., Alverson, D.L., Metuzals, K., 2000. By-catch: problems and solutions. Mar. Pollut. Bull. 41, 204-219.

Harris, A.N., Poiner, I.R., 1990. By-catch of the Prawn Fishery of Torres Strait; composition and partitioning of the discards into components that float or sink. Aust. J. Mar. Freshw. Res. 41, 37-52.

Heales, D.S., Brewer, D.T., Wang, Y.G., 2000. Subsampling multi-species trawl catches from tropical northern Australia: Does it matter which part of the catch is sampled? Fish. Res. 48, 117-126.

Kennelly, S.J., Liggins, G.W., Broadhurst, M.K., 1998. Retained and discarded by-catch from oceanic prawn trawling in New South Wales, Australia. Fish. Res. 36, 217-236.

Milton, D.A., 2001. Assessing the susceptibility to fishing of populations of rare trawl bycatch: sea snakes caught by Australia's Northern Prawn Fishery. Biol. Conserv. 101, 281-290.

Montgomery, D.C., 1997. Design and Analysis of Experiments, 4th ed. John Wiley and Sons.

Pascoe, S., 1997. Bycatch management and the economics of discarding. FAO Fish. Tech. Pap. 370, p. 137.

Robins, J., Courtney, A., 1998. Status report on bycatch within the Queensland trawl fishery. In Buxton, C., Eayrs, S. (eds.) Establishing meaningful targets for bycatch reduction in Australian fisheries, Australian Society for Fish Biology, Sydney. Hobart 24-25 September 1998.

Robins, J., Campbell, M., McGilvray, J., 1999. Reducing prawn-trawl bycatch in Australia: an overview and an example from Queensland. Mar. Fish. Rev. 61, 46-55.

Robins, J., Eayrs, S., Campbell, M., Day, G., McGilvray, J., 2000. Commercialisation of bycatch reduction strategies and devices within northern Australian prawn trawl fisheries. Fisheries Research and Development Corporation Final Report. FRDC Project Number 96/254.

Steele, P., Bert, T.M., Johnston, K.H., Levett, S., 2002. Efficiency of bycatch reduction devices in small otter trawls used in the Florida shrimp fishery. Fish. Bull. 100, 338-350.

Sterling, D.J., 2005. Modelling the Physics of Prawn Trawling For Fisheries Management. Curtin University of Technology, Western Australia, Perth.

Stobutzki, I., Miller, M., Jones, P., Salini, J., 2001. Bycatch diversity and variation in a tropical Australian penaeid fishery; the implications for monitoring. Fish. Res. 53, 283-301.

Ward, T.M., 1996. Sea snake by-catch of prawn trawlers on the northern Australian continental shelf. Mar. Freshw. Res. 47, 631-5.

Wassenberg, T.J., Salini, J.P., Heatwole, H., Kerr, J.D., 1994. Incidental capture of sea-snakes (Hydrophiidae) by prawn trawlers in the Gulf of Carpentaria, Australia. Aust. J. Mar. Freshw. Res. 45, 429-443.

Watson, J.W., Taylor, C.W., 1988. Research on selective shrimp trawl designs for penaeid shrimp in the United States: A review of selective shrimp trawl research in the United States since 1973. In: FAO expert consultation on selective shrimp trawl development, Mazatlan, Mexico, 24-28 November 1986, FAO Rome, 1986.

Watson, R.A., Dredge, M.L.C., Mayer, D.G., 1990. Spatial and seasonal variation in demersal trawl fauna associated with a prawn fishery on the central Great Barrier Reef, Australia. Aust. J. Mar. Freshw. Res. 41, 65-77.

Williams, L.E., 2002. Queensland's Fisheries Resources: current condition and recent trends 1988-2000 Queensland Department of Primary Industries, Information Series QI02012. Department of Primary Industries, Brisbane.

Ye, Y., Alsaffar, A., Mohammed, H., 2000. Bycatch and discards of the Kuwait shrimp fishery. Fish. Res. 45, 9-19.

6 Quantifying the effects of bycatch reduction devices in the north Queensland tiger/endeavour prawn fishery

A. J. Courtney, C. van der Geest, C. Rose, C. T. Turnbull, M. J. Campbell, D. P. Roy, M. L. Tonks, and P. M. Kyne

6.1 ABSTRACT

This chapter presents results from an eight-day research charter that quantified the effects of a turtle excluder device (TED) and radial escape section bycatch reduction device (BRD) on marketable prawn and bycatch rates in the north Queensland tiger/endeavour prawn fishery. There were 317 taxa recorded in the bycatch, based on 192 sub-samples. Dominant species groups were flatfish, cardinalfish, lizardfish, catfish, dragonets, leatherjackets, toadfish, ponyfish, goatfish, and non-targeted penaeid prawns and portunid crabs. Multidimensional scaling and analysis of similarities showed that bycatch assemblages varied strongly with latitude, and to a lesser extent with depth, but not with codend treatment type. When the TED and radial escape section BRD were used together, bycatch rates were reduced significantly by 20%, with no significant loss of marketable size prawns. The largest reduction in bycatch rate was 36% for the naked headed catfish *Euristhmus nudiceps*. Fish species that showed significant reductions in catch rate that were attributed to the TED, the radial escape section BRD or both devices together, were all larger than 70 mm in length. While the 20% reduction in bycatch rate is encouraging it was lower than expected, probably because of the inability of many small fish species to swim forward and out of the large escape meshes due to the relatively high speeds (i.e., > 3 knots) at which trawling for tiger prawns occurs.

6.2 INTRODUCTION

The north Queensland tiger/endeavour prawn fishery is a major component of the state's trawl fishery and located in coastal waters north of 22^{o} S. Catches of tiger and endeavour prawns also occur south of this latitude, but they are relatively minor. The fishery is regulated, and spatially defined by, an annual closure from 15 December to 1 March which extends from the tip of Cape York Peninsula (11^{o} S) south to 22^{o} S to depths of approximately 100 m (50 fm). The major targeted species are tiger prawns (*Penaeus esculentus* and *Penaeus semisulcatus*) and endeavour prawns (*Metapenaeus endeavouri* and *Metaepenaeus ensis*), but several other prawn species are also taken including redspot king prawns (*Penaeus longistylus*), blue-legged or western king prawns (*Penaeus latisulcatus*), eastern king prawns (*Penaeus plebejus*), banana prawns (*Penaeus merguiensis*), black tiger prawns (*Penaeus monodon*) and reef-associated velvet prawns (*Metapenaeopsis palmensis* and *Metapenaeopsis rosea*). Moreton Bay bugs (*Thenus orientalis* and *Thenus indicus*) are an important byproduct of the fishery which can also be targeted, retained and marketed. Logbook data for the period 1988 to 2003 indicate an average of about 4200 tonnes of tiger, endeavour, banana and king prawns was caught annually by otter trawlers from the fishery from an average of 42,600 boat-days.

Despite the fishery's large spatial area, the large amount of fishing effort it attracts and the high value of the catch ($50+ million annually) relatively little research has been undertaken on the fishery's bycatch. The impacts of turtle excluder devices

(TEDs) and bycatch reduction devices (BRDs) on bycatch rates, which were made mandatory in the period 2000 to 2002, have not been assessed. A monthly research trawl survey was used to describe the benthic faunal community in the fishery between 18^o S and 20^o S in 1985 and 1986 (Jones and Derbyshire, 1988; Watson and Goeden, 1989; Watson et al., 1990). While these samples were not obtained from commercial trawlers (i.e., they were obtained using the QDPI&F Research Vessel *Gwendoline May*) the species composition is likely to be very similar to that of the commercial fishery bycatch. Watson et al. (1990) recorded 477 species in the demersal fauna which were broadly classified into three spatial community groupings across the shelf: nearshore (2–5 m), shallow offshore (6–14 m) and deep offshore (15–35 m). Shortly before TEDs and BRDs were made mandatory in the Queensland trawl fishery, Robins et al. (2000) undertook an extension project aimed at encouraging trawl fishers to trial the devices. During that project several different TEDs and BRDs were loaned out to fishers on the Queensland east coast, Torres Strait and the Northern Prawn Fishery in the Gulf of Carpentaria. Fishers participating in the project provided feedback on their performance and one device that showed potential for reducing bycatch while maintaining prawn catch rates was the radial escape section BRD.

The objective of this chapter was similar to that of Chapter 5, that is, to quantify the effects of the a) radial escape section BRD, b) TED and c) both devices used together on the catch rates of bycatch and targeted prawns in the north Queensland tiger/endeavour prawn fishery.

6.3 MATERIALS AND METHODS

The weighing and sub-sampling of the catches, experimental design and statistical methods were similar to those described in Chapter 5. Where differences in the methodology occurred they were described in the appropriate sections below.

6.3.1 Spatial distribution of sampling

The effects of the devices were evaluated using a dedicated research charter and to this end, the QDPI&F Research Vessel *Gwendoline May* was chartered for eight nights between 9 and 19 May 2002. To ensure the bycatch and prawn catch rates and composition were representative of the fleet, all trawling was located in 30 minute x 30 minute logbook grids that receive relatively high levels of fishing effort in the tiger/endeavour prawn fishery (grids H15 and H16 north of Cairns, grids G12 and G13 Cape Flattery and grids D10, D11 and E11 Princess Charlotte Bay, see Figure 6.4.1). Each trawl was precisely two nautical miles long and conducted in a straight path to ensure all nets swept the same size area. The location of the trawl sites and the time required to travel between them facilitated six sites being trawled each night.

6.3.2 TED and BRD codend treatments

The vessel was rigged to tow four 4-fathom 4-seam Florida Flyer nets, which is similar to, and representative of, many commercial trawlers operating in the fishery. Four treatment codends (same as those in Chapter 5) were compared: (1) standard codend only (considered as an experimental “control” net), (2) standard codend with TED only, (3) standard codend with radial escape section BRD only, and (4) standard codend with both TED and radial escape section BRD.

The body of the nets was constructed of 2-inch, 24-ply polyethylene. The standard codend was constructed of 1¾-inch mesh using 48-ply polyethylene and was 100 meshes round and 100 meshes long with a 25-mesh skirt. The TED was the same as that used in Chapter 5, except that it was installed at 55 degrees from the horizontal (see Figure 5.3.1E). The radial escape section BRD was the same as that used in Chapter 5, except that the large 200 mm (8-inch) meshes through which the bycatch escapes were sewn around the entire circumference of the radial escape section (see Figure 5.3.1B and Figure 5.3.2). The ground chain was constructed of 8 mm galvanised chain with seven 10 mm droppers and four 8 mm droppers.

Because the vessel towed four nets, all four codend types could be tested simultaneously during each trawl, thus facilitating a "complete block" experimental design (Montgomery, 1997) which is more robust than the incomplete block design used for triple gear in Chapter 5. At the completion of each night of sampling the codends were cut off and sewn onto a different net, as per a predetermined treatment protocol (Table 6.3.1) that was based on two Latin square designs (also known as a back-to-back Latin square design), such that each codend type was tested in each net position on two nights.

Table 6.3.1. The codend treatment protocols applied during the north Queensland tiger/endeavour prawn charter, based on a back-to-back Latin square design. Each codend type was tested in each net position on two nights.

Night	Outer Port	Inner Port	Inner Starboard	Outer Starboard
1	Standard codend	Radial escape section BRD	TED only	Radial escape section BRD and TED
2	TED only	Standard codend	Radial escape section BRD and TED	Radial escape section BRD
3	Radial escape section BRD	Radial escape section BRD and TED	Standard codend	TED only
4	Radial escape section BRD and TED	TED only	Radial escape section BRD	Standard codend
5	TED only	Standard codend	Radial escape section BRD	Radial escape section BRD and TED
6	Standard codend	Radial escape section BRD	Radial escape section BRD and TED	TED only
7	Radial escape section BRD	Radial escape section BRD and TED	TED only	Standard codend
8	Radial escape section BRD and TED	TED only	Standard codend	Radial escape section BRD

6.3.3 Measuring and sampling the catch

Methods for sorting and weighing catches, obtaining a representative sub-sample of the bycatch, measuring the lengths of prawns and bycatch species, and converting all catch estimates to catch (in weight) per swept area are identical to those in Chapter 5.

All prawns were retained, labelled and frozen at sea, returned to the laboratory, sorted to species and sex, and measured to the nearest whole mm carapace length (CL). Prawn lengths were then converted to weights using species- and sex-specific carapace–weight relationships. The effect of codend type on the weight of marketable prawns was analysed. To estimate the area swept by each net a net spread factor for quad gear of 0.70 was used, based upon the Prawn Trawl Performance Model of Sterling (2000).

6.3.4 Statistical design and analyses

The same generalised linear modelling approach was used to examine variation in a) catch rates (g ha^{-1}) and b) length (mm) for both prawns and bycatch, as per Chapter 5. The only difference was that the "side-of-boat" term was expanded to include four levels of net position (i.e., inner port, outer port, inner starboard and outer starboard).

Multidimensional scaling was used to examine variation in the bycatch faunal community structure, using the same methodology described in Chapter 5. The only difference was that depths were rounded to the nearest 5 m (rather than 10 m), due to the shallower and narrower range of depths sampled. Effects due to depth, latitude and codend type on bycatch community structure were examined.

6.3.5 Bycatch species catch rates and power analysis

In addition to testing the effect of the codend type on bycatch species, outputs from the generalised linear modelling were used to examine the statistical power required to detect change in bycatch species catch rates, should a bycatch monitoring program be implemented. The mean observed catch rate of individual bycatch species from the standard net (i.e., with no TED and no BRD) and the mean square value (i.e., variance) derived from the generalised linear model output were used to estimate the power required to detect change. Two possible monitoring program scenarios were examined: one based on a sampling program of 30 trawl samples, and the other based on 300 trawl samples. Two levels of change were also considered: a 40% reduction in mean catch rate and an 80% reduction. A commonly used probability of 0.8 for power analysis was used based on the discussion by Snedecor and Cochran (1967).

6.4 RESULTS

6.4.1 Catch rates and the effects of bycatch reduction devices

A total of 48 two-nautical mile trawls (Figure 6.4.1) were successfully completed producing a total of 192 (8 nights x 6 trawls per night x 4 nets per trawl) measurements of bycatch and prawn catch rates. Because all four codend types were deployed during each trawl the charter produced 48 measurements of prawn and bycatch catches for each codend type. Trawl speed was fixed at 3.2 knots. The depth of the sites trawled ranged between 13.9 and 27.2 m.

A total of 17,521 prawns were caught. The most numerous species was the red endeavour prawn *Metapenaeus ensis* which comprised 52.3% of the prawn catch, followed by the grooved tiger prawn *Penaeus semisulcatus* (18.8%), then by the brown tiger prawn *Penaeus esculentus* (13.2%), then by the red spot king prawn *Penaeus longistylus* (10.1%), then by the blue-legged king prawn *Penaeus* *latisulcatus* (4.1%) and the blue tail endeavour prawn *Metapenaeus endeavouri* (1.1%). Individual prawn weights were estimated using species- and sex-specific carapace length-weight relationships. Only marketable size prawns were included in the analyses, which equated to individuals that were 15 g or larger (i.e., the minimum commercial size grade of "30 count per pound"). Species and sexes were then pooled and their weights summed to derive a single estimate of the weight of marketable prawns from each net for each trawl (i.e., 48 trawls x 4 nets = 192 measures of marketable prawn catch).

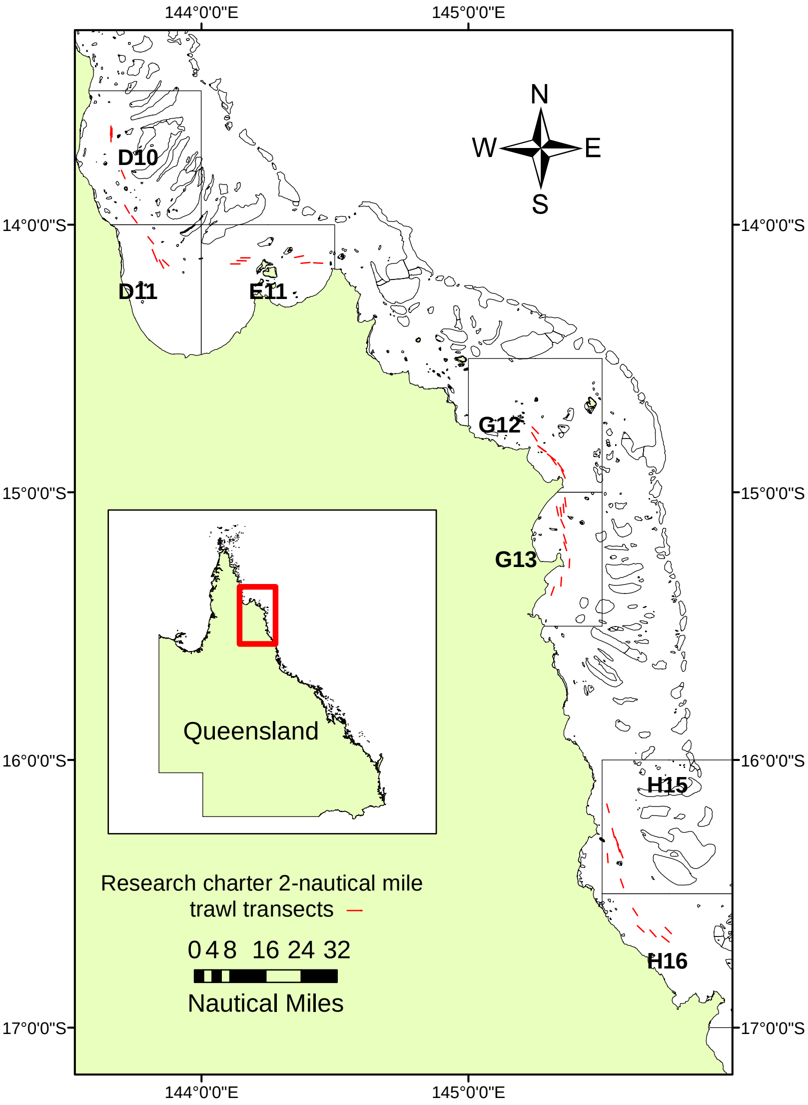


Figure 6.4.1. Location of the 48 two-nautical mile trawl transects sampled during the north Queensland tiger/endeavour prawn charter in May 2002. The vessel towed four nets (i.e., quad gear) simultaneously resulting in 192 (i.e., 48 trawls x 4 nets) measurements of bycatch and prawn catches. Location of the 30' x 30' logbook grids is also provided.

A total of 317 taxa were identified in the 192 bycatch sub-samples, with most species being relatively uncommon. For example, 230 taxa (73% of species) occurred in fewer than 10% of the sub-samples and 95 taxa (30% of species) were found in only one sub-sample. The 10 species with the highest mean catch rates, from all net types pooled, were the red spot monocle bream *Scolopsis taeniopterus* (601.97 g ha^{-1}), the crab *Charybdis truncata* (226.55 g ha^{-1}), the Japanese flathead *Inegocia japonica* (150.75 g ha^{-1}), the lizardfish *Saurida grandisquamis* (138.70 g ha^{-1}), the silver toadfish *Lagocephalus sceleratus* (122.62 g ha^{-1}), the purple-spotted bigeye *Priacanthus tayenus* (120.79 g ha^{-1}), ochreband goatfish *Upeneus sundaicus* (107.67 g ha^{-1}), the sunrise goatfish *Upeneus sulphureus* (96.98 g ha^{-1}), the longspine emperor *Lethrinus genivittatus* (96.22 g ha^{-1}) and the portunid crab *Portunus tenuipes* (95.62 g ha^{-1}).

A complete list of 525 species that the project recorded from the bycatch of the north Queensland tiger/endeavour prawn fishery, and their catch rates, is provided in Appendix 2. The list includes the 317 taxa recorded from the research charter and additional species recorded in opportunistic samples obtained from vessels operating in the sector.

Overall mean catch rates from all net types were 4.08 kg ha^{-1} (S.E. 0.34) for bycatch and 0.77 kg ha^{-1} (S.E. 0.03) for marketable size prawns. As a general observation, the bycatch rate was low compared to that for the shallow water eastern king prawn charter reported in Chapter 5 (i.e., 9.56 kg ha^{-1} refer to section 5.4.1). A single flatback turtle was caught in the codend that had no TED or radial escape section BRD installed (Figure 6.4.2). The weight of the turtle was estimated at 65 kg and included in the bycatch weight measures for subsequent analyses. The turtle was returned to the water alive shortly after being caught.

Figure 6.4.2. The flatback turtle (*Natator depressus*) caught aboard the QDPI&F RV *Gwendoline May* during the charter undertaken in the north Queensland tiger/endeavour prawn fishery. The turtle was caught in the standard net (i.e., no TED or BRD installed). Note the partitioning of the sorting tray which facilitated separate, and therefore more accurate, processing and measuring of the catch from the four nets.

The observed mean catch rates from the standard net were 4.85 kg ha^{-1} (S.E. 0.82) for total bycatch and 0.80 kg ha^{-1} (S.E. 0.05) for marketable prawns (Table 6.4.1). The codend with the TED-only significantly ($P < 0.05$) reduced the bycatch rate by 14% ($\boldsymbol{\beta}_3$ parameter estimate of 0.86, Table 6.4.1). The 11% ($\boldsymbol{\beta}_3$ parameter estimate of 0.89, Table 6.4.1) reduction in bycatch rate from the net with the radial escape section only was not statistically significant. When both devices were used together the bycatch rate was significantly reduced by 20% ($\boldsymbol{\beta}_3$ parameter estimate of 0.80, $P < 0.05$, Table 6.4.1) compared to the standard net. None of the devices had a significant effect on the catch rate of marketable prawns (Table 6.4.1).

Net position (i.e., inner port, outer port, inner starboard or outer starboard) was found to have a significant effect ($P < 0.05$) on bycatch and marketable prawn catch rates and was therefore included in the models. The net position effect was probably due to the way the nets and otter boards were set up and tuned by the crew. The interaction term “net position x codend type” was not significant for either bycatch or marketable prawn catch rates and therefore the results presented herein, which are limited to codend type main effects, are robust.

Table 6.4.1. The effects of the radial escape section BRD and TED on the catch rates of bycatch and marketable size prawns based on 192 individual net tows (48 trawls x 4 nets). Generalised linear modelling was used to quantify codend treatment effects. Significant differences between treatments ($P < 0.05$) are bolded and identified by different alphabetic characters (A, B, C or D). Parameter estimates were proportionally scaled so they can be compared to a standard net parameter value of 1. Standard errors in parentheses.

Response variable	**Mean observed catch rate in kg ha^{-1} Standard net**	**Predicted change in catch rates based on generalised linear model parameter estimates (proportionally scaled to a Standard net parameter value of 1)**			**Distribution type**
		TED only	**Radial escape section BRD only**	**Radial escape section BRD and TED together**	
Total Bycatch	**4.85 (0.82) A**	**0.86 (0.06) B**	**0.89 (0.06) A**	**0.80 (0.05) B**	**Gamma**
Marketable prawns	0.80 (0.05)	0.98 (0.01)	0.96 (0.01)	0.90 (0.02)	Normal (square-root transformed)

6.4.2 Effects of codend type on bycatch species

Because most species were relatively uncommon, resulting in a high incidence of zero catch rates, it was not possible to determine the effect of the codend type on all species. Analyses were therefore undertaken on 37 species that comprised 90% of the weight of the bycatch in the standard net (Table 6.4.2). Of these, significant reductions in catch rates were detected for eight species that were attributed to the TED, the radial escape section BRD, or both devices used together. The largest significant reduction was detected for the naked headed catfish *Euristhmus nudiceps,* which was present in 50% of sub-samples. When the TED and radial escape section BRD were used together, catfish catch rates fell by 36% ($\boldsymbol{\beta}_3$ parameter estimate of 0.64, Table 6.4.2). Relatively large reductions were also detected for Whitley’s toadfish *Torquigener whitleyi* (31% reduction, $\boldsymbol{\beta}_3$ parameter estimate of 0.69), the freckled goatfish *Upeneus tragula* (29% reduction, $\boldsymbol{\beta}_3$ parameter estimate of 0.71) and the mud scallop *Amusium pleuronectes* (26% reduction, $\boldsymbol{\beta}_3$ parameter estimate of 0.74) in codends that contained both the TED and radial escape section BRD. A relatively large and significant reduction of 34% was detected for the longspine emperor *Lethrinus genivittatus* ($\boldsymbol{\beta}_3$ parameter estimate of 0.66, Table 6.4.2) from the codend with the radial escape section BRD only. No significant effects were detected for the prawns (*Metapenaeopsis palmensis, Trachypenaeus anchoralis* and *Trachypenaeus granulosus*) or crab (*Portunus tenuipes*), which is consistent with the conclusions of Chapter 5, that is, that the radial escape section BRD appears to have little effect on crustacean catch rates.

Surprisingly, of the 37 species analysed, significant *increases* in catch rates that were attributed to the TED, the radial escape section BRD or both devices used together, were detected for five species. For example, both ponyfishes *Leiognthus* sp. *2* and *Leiognathus splendens* experienced significant increases in catch rate when TEDs were present in the codends, compared to the standard net. The radial escape section BRD by itself had no significant effect on ponyfish catch rates. Catch rates of the short finned lizardfish *Saurida micropectoralis* increased by 73% ($\boldsymbol{\beta}_3$ parameter estimate of 1.73, Table 6.4.2) in the net that had both the radial escape section BRD and TED, compared to the standard net. Catch rates of the dusky leatherjacket *Paramonacanthus otisensis* and the flatfish *Pseudorhombus diplospilus* increased significantly, by 57% and 31% respectively in the codend with the radial escape section BRD. Such increases are difficult to explain and for some species may be an anomaly attributed to small sample size. For example, the ponyfish *L. splendens* was only present in 12% of the 192 sub-samples (i.e., 23 sub-samples) and it is quite feasible that the results were influenced by one or more observations where a net sampled a large patch or school.

The effect of the codend type on mean length of the bycatch species was highly variable. Of the 37 species examined, 11 experienced a significant effect due to the TED, the radial escape section BRD or both devices used together (Table 6.4.3). Six species experienced a significant increase and five species experienced a significant decrease. The results suggest that the devices affect species differently, and that for some species, it is the larger individuals that escape via the devices, and for other species it is the smaller individuals that are excluded.

Table 6.4.2. Effects of codend type on the catch rates of the more commonly encountered bycatch species based on 192 measures (48 sites trawled x 4 nets). Generalised linear modelling was used to quantify the effects. Significant differences between codends ($P < 0.05$) are bolded and identified by different alphabetic characters (A, B, C or D). Distribution types used in the models were N = normal, G = gamma and B = binomial. For normal and gamma distributed data, the parameter estimates have been proportionally scaled so they could be compared to a standard net parameter value of 1. All binomial data are probabilities of capture. Standard errors in parentheses.

				Predicted change in catch rates based on generalised linear model			
Species	**Occurrence (%) in 192 sub-samples (48 trawls x 4 nets)**	**Mean observed catch rate (g ha^{-1}) in the standard net**	**Predicted probability of occurrence in the standard net**	**TED only**	**Radial escape section BRD only**	**Radial escape section BRD and TED together**	**Distribution type**
Metapenaeopsis palmensis	98	40.14 (5.30)	*	0.82(0.08)	0.86 (0.08)	0.93 (0.09)	G
Scolopsis taeniopterus	**97**	**706.20 (128.10) A**	*****	**1.06 (0.13) A**	**0.77 (0.09) B**	**0.90 (0.11) AB**	**N(log)**
Inegocia japonica	**93**	**168.18 (24.36) A**	*****	**0.75 (0.07) B**	**0.77 (0.08) B**	**0.96 (0.10) A**	**G**
Portunus tenuipes	91	97.22 (14.88)	*	0.95 (0.11)	1.08 (0.13)	1.02 (0.12)	G
Apogon fasciatus	90	98.28 (22.80)	*	1.12 (0.28)	1.00 (0.25)	1.23 (0.30)	N(log)
Upeneus sundaicus	**90**	**98.52 (17.58) AB**	*****	**1.23 (0.18) A**	**1.22 (0.17) AB**	**0.89 (0.13) B**	**G**
Charybdis truncate	89	254.00 (76.10)	*	0.89 (0.08)	0.98 (0.09)	0.85 (0.08)	G
Apogon ellioti	87	21.76 (3.13)	*	1.02 (0.34)	0.95 (0.32)	0.70 (0.23)	N(log)
Apogon poecilopterus	82	32.70 (5.58)	*	0.76 (0.12)	0.94 (0.15)	0.87 (0.13)	G
Saurida grandisquamis	82	147.91 (20.99)	*	0.91 (0.11)	0.82 (0.10)	0.79 (0.10)	G
Lagocephalus sceleratus	**82**	**126.87 (43.04) A**	*****	**1.22 (0.15) B**	**0.86 (0.10) A**	**0.92 (0.11) A**	**G**
Callionymus grossi	81	56.59 (8.74)	*	1.01 (0.10)	0.99 (0.10)	0.96 (0.10)	G
Suggrundus macracanthus	80	26.33 (4.38)	*	0.83 (0.16)	1.13 (0.22)	0.98 (0.19)	G
Priacanthus tayenus	77	151.52 (27.05)	*	0.77 (0.19)	0.55 (0.14)	0.45 (0.11)	N(log)
Trachypenaeus anchoralis	76	24.14 (4.35)	*	1.09 (0.14)	1.08 (0.14)	0.91 (0.11)	G
Paramonacanthus otisensis	**73**	**19.71 (4.33) A**	*****	**1.07 (0.22) AC**	**1.57 (0.32) B**	**1.47 (0.30) C**	**N(log)**
Amusium pleuronectes	**68**	**50.37 (7.97) A**	*****	**0.97 (0.10) A**	**0.85 (0.09) AB**	**0.74 (0.08) B**	**G**
Upeneus sulphureus	60	102.52 (28.21)	*	1.12 (0.12)	0.91 (0.10)	0.94 (0.11)	G
Callionymus belcheri	59	12.66 (3.56)	*	0.99 (0.29)	0.87 (0.26)	0.89 (0.26)	N(log)
Trachypenaeus granulosus	54	13.99 (3.55)	*	0.92 (0.31)	0.88 (0.30)	1.24 (0.42)	N(log)
Apistus carinatus	53	24.66 (13.14)	*	1.10 (0.27)	0.89 (0.22)	1.18 (0.29)	N(log)
Saurida micropectoralis	**53**	**77.28 (16.92) A**	*****	**1.30 (0.29) AB**	**1.34 (0.29) AB**	**1.73 (0.37) B**	**G**
Torquigener whitleyi	**52**	**30.40 (8.35) A**	*****	**0.96 (0.12) A**	**1.06 (0.14) A**	**0.69 (0.09) B**	**G**

Species	**Occurrence (%) in 192 sub-samples (48 trawls x 4 nets)**	**Mean observed catch rate (g ha^{-1}) in the standard net**	**Predicted probability of occurrence in the standard net**	**Predicted change in catch rates based on generalised linear model**			**Distribution type**
				TED only	**Radial escape section BRD only**	**Radial escape section BRD and TED together**	
Euristhmus nudiceps	**50**	**52.10 (14.32) A**	*****	**0.97 (0.16) A**	**0.91 (0.15) A**	**0.64 (0.10) B**	**G**
Pseudorhombus diplospilus	**35**	**38.80 (14.80) AB**	*****	**0.63 (0.18) A**	**1.31 (0.38) B**	**1.05 (0.30) B**	**G**
Leiognathus* sp. *2	**34**	**16.15 (7.29) A**	*****	**2.05 (0.64) B**	**1.60 (0.51) AB**	**2.17 (0.68) B**	**N(log)**
Upeneus tragula	**31**	**26.98 (9.18) AB**	*****	**1.24 (0.32) A**	**0.92 (0.24) AB**	**0.71 (0.19) B**	**G**
Pseudorhombus arsius	30	26.27 (6.44)	*	0.99 (0.24)	0.91 (0.22)	1.25 (0.31)	G
Pseudorhombus spinosus	30	*	0.32 (0.05)	0.32 (0.05)	0.29 (0.05)	0.25 (0.05)	B
Synodus hoshinonis	30	17.80 (4.89)	*	0.99 (0.21)	1.16 (0.27)	0.93 (0.22)	G
Lethrinus genivittatus	**28**	**97.19 (55.39) A**	*****	**0.81 (0.13) AB**	**0.66 (0.10) B**	**0.75 (0.12) B**	**N(log)**
Psettodes erumei	28	*	0.29 (0.05)	0.18 (0.04)	0.23 (0.05)	0.39 (0.05)	B
Sillago maculate	26	11.91 (4.86)	*	1.12 (0.17)	1.18 (0.20)	0.96 (0.15)	N(log)
Siganus fuscescens	25	24.52 (16.77)	*	0.94 (0.13)	0.95 (0.13)	0.89 (0.12)	N(log)
Choerodon cephalotes	15	*	0.13 (0.03)	0.12 (0.03)	0.15 (0.03)	0.19 (0.03)	B
Leiognathus splendens	**12**	**24.63 (15.02) A**	*****	**1.18 (0.09) B**	**1.01 (0.08) A**	**1.09 (0.08) AB**	**N(log)**
Pentapodus paradiseus	8	*	0.09 (0.02)	0.04 (0.11)	0.09 (0.02)	0.10 (0.02)	B

Table 6.4.3. Effects of the TED and radial escape section BRD on the length of the more common bycatch species encountered in the research charter undertaken in the north Queensland tiger/endeavour prawn fishery. Significant effects (P < 0.05) are bolded. Analyses were undertaken using normally distributed length measures. Treatments with the same alphabetic character (A, B, C or D) were not significantly different. Standard errors in parentheses.

		Predicted mean length (mm) based on generalised linear model			
Species	**Occurrence (%) in 192 sub-samples (48 trawls x 4 nets)**	**Standard net**	**TED only**	**Radial escape section BRD only**	**Radial escape section BRD and TED together**
Metapenaeopsis palmensis	**98**	**14.00 (0.18) A**	**14.11 (0.18) A**	**14.81 (0.18) B**	**13.93 (0.18) A**
Scolopsis taeniopterus	**97**	**103.23 (1.12) A**	**101.16 (1.10) AB**	**98.34 (1.21) B**	**99.89 (1.13) B**
Inegocia japonica	**93**	**123.03 (1.47) AB**	**120.74 (1.59) A**	**126.27 (1.58) B**	**120.80 (1.47) A**
Portunus tenuipes	**91**	**42.26 (0.28) A**	**41.48 (0.27) B**	**41.90 (0.28) AB**	**41.99 (0.28) AB**
Apogon fasciatus	90	60.68 (0.98)	60.88 (1.00)	62.36 (1.05)	60.25 (0.96)
Upeneus sundaicus	90	107.60 (1.23)	109.54 (1.07)	109.28 (1.09)	107.63 (1.14)
Charybdis truncate	89	40.48 (0.38)	39.94 (0.38)	40.62 (0.39)	40.70 (0.39)
Apogon ellioti	87	58.32 (1.73)	60.55 (1.76)	62.53 (1.89)	59.38 (1.82)
Apogon poecilopterus	82	58.10 (1.34)	59.85 (1.53)	60.59 (1.42)	60.14 (1.41)
Saurida grandisquamis	82	180.56 (2.75)	181.78 (2.69)	179.98 (2.81)	180.42 (2.83)
Lagocephalus sceleratus	82	106.29 (1.13)	107.12 (1.09)	106.99 (1.22)	106.07 (1.18)
Callionymus grossi	81	115.28 (1.10)	117.42 (1.07)	116.13 (1.09)	116.60 (1.13)
Suggrundus macracanthus	80	103.73 (2.25)	98.56 (2.37)	100.12 (2.12)	100.98 (2.20)
Priacanthus tayenus	77	141.35 (2.55)	137.26 (2.44)	138.63 (2.78)	136.01 (2.94)
Trachypenaeus anchoralis	**76**	**14.79 (0.25) A**	**15.38 (0.26) AB**	**15.63 (0.25) B**	**15.05 (0.26) AB**
Paramonacanthus otisensis	73	67.48 (1.18)	67.55 (1.15)	65.22 (1.10)	65.52 (1.10)
Amusium pleuronectes	68	49.46 (0.45)	50.05 (0.45)	49.19 (0.48)	48.93 (0.47)
Upeneus sulphureus	60	87.09 (0.96)	87.10 (0.91)	87.80 (1.02)	87.62 (0.96)
Callionymus belcheri	59	82.34 (1.73)	79.83 (1.53)	82.69 (1.82)	81.71 (1.82)
Trachypenaeus granulosus	54	14.68 (0.36)	15.03 (0.37)	14.48 (0.39)	14.60 (0.33)
Apistus carinatus	53	67.75 (2.44)	67.42 (2.46)	65.50 (2.57)	65.86 (2.24)
Saurida micropectoralis	53	223.86 (10.16)	220.51 (8.18)	219.82 (8.49)	228.22 (7.76)
Torquigener whitleyi	52	78.36 (1.62)	80.84 (1.52)	79.49 (1.57)	76.99 (1.52)

Species	**Occurrence (%) in 192 sub-samples (48 trawls x 4 nets)**	**Predicted mean length (mm) based on generalised linear model**			
		Standard net	**TED only**	**Radial escape section BRD only**	**Radial escape section BRD and TED together**
Euristhmus nudiceps	50	222.53 (5.09)	212.18 (4.98)	221.89 (5.21)	211.28 (5.20)
Pseudorhombus diplospilus	**35**	**178.16 (6.83) AB**	**174.02 (7.39) B**	**187.31 (6.01) AB**	**194.77 (5.79) A**
Leiognathus **sp. 2**	**34**	**56.16 (2.05) A**	**63.31 (1.51) B**	**62.67 (1.94) B**	**60.55 (1.58) AB**
Upeneus tragula	**31**	**92.33 (1.81) AB**	**94.83 (2.05) A**	**91.39 (2.33) AB**	**88.23 (2.37) B**
Pseudorhombus arsius	30	197.61 (4.85)	202.41 (6.89)	196.96 (5.78)	183.93 (5.32)
Pseudorhombus spinosus	**30**	**172.52 (6.08) AB**	**189.75 (6.56) B**	**162.42 (6.09) A**	**171.75 (5.57) A**
Synodus hoshinonis	30	124.26 (1.95)	120.98 (1.90)	124.30 (2.27)	125.41 (2.14)
Lethrinus genivittatus	28	108.86 (2.82)	104.92 (2.73)	106.71 (3.62)	108.18 (3.14)
Psettodes erumei	28	198.50 (13.90)	211.70 (20.60)	232.90 (17.20)	216.40 (11.50)
Sillago maculate	26	158.51 (4.85)	158.04 (4.92)	156.74 (5.18)	152.03 (5.26)
Siganus fuscescens	**25**	**115.73 (3.20) A**	**108.09 (3.05) B**	**97.23 (4.52) B**	**102.92 (2.96) B**
Choerodon cephalotes	15	120.49 (5.13)	117.23 (4.28)	115.60 (5.65)	107.81 (4.35)
Leiognathus splendens	12	68.83 (2.91)	66.48 (2.35)	65.71 (2.28)	68.84 (2.18)
Pentapodus paradiseus	**8**	**116.21 (6.28) A**	**67.59 (12.11) B**	**117.26 (7.89) AB**	**109.09 (6.74) A**

6.4.3 Variation in bycatch community structure and the effects of the TED and radial escape section BRD

Multidimensional scaling (MDS) was carried out using all 192 bycatch sub-samples and the catch rates of 122 species that were present in 5% or more sub-samples. The remaining species were not included due to high incidences of zero catch rates. The resulting stress value was 0.24 for a two-dimensional ordination (Figure 6.4.3A–C).

Analysis of similarities (ANOSIM) indicated that, although the range of depths sampled was relatively narrow (i.e., 13.9 to 27.2 m), there was a significant difference in bycatch assemblages between depths (global $R = 0.173$, $P < 0.001$), with the largest difference between the shallowest and deepest categories. Clustering of sites from the same depth categories is apparent in Figure 6.4.3A. It is noteworthy that the global *R*-statistic was much lower than that obtained for the similar depth analysis undertaken for the shallow water eastern king prawn analysis (see section 5.4.2), probably because of the relatively narrow depth range.

The pairwise test for the < 15 m and 26–30 m groups resulted in an *R*-statistic of 0.872 ($P < 0.001$). Species that accounted for relatively high proportions of the dissimilarity between these two depth categories included the naked headed catfish *E. nudiceps*, which contributed 5.09% of dissimilarity, the ponyfish *L. splendens* (4.89%) and the Australian halibut *P. erumei* (3.12%) which were all abundant in the shallow water sites, and the purple-spotted bigeye *P. tayenus* (5.01%), the sunrise goatfish *U. sulphureus* (4.00%) and the lizardfish *S. micropectoralis* (3.20%) which were largely restricted to the deeper category (i.e., 26–30 m).

Bycatch assemblages were also strongly affected by latitude (global *R*-statistic = 0.540, $P < 0.001$). This was not surprising given that the sample sites were distributed over a relatively large latitudinal range; the most northern site was located at $13^{o}14.106'$ S and the southernmost site at $16^{o}40.838'$ S (Figure 6.4.1). *R*-statistic values for each pairwise test of latitudinal groups are provided in Table 6.4.4. The largest differences were found between the 13.5 and 16.0 latitudinal groups (*R*-statistic = 1.000), followed by the 15.5 and 13.5 groups (*R*-statistic = 0.814), then by the 13.5 and 16.5 groups (*R*-statistic = 0.795) and the 15.5 and 14.0 groups (*R*-statistic = 0.771). Clustering of samples, based on latitudinal groups, is apparent in Figure 6.4.3B. Species that contributed most to the dissimilarity between the northernmost (13.5) and southernmost (16.5) latitudinal groups were the lizardfish *S. grandisquamis* which contributed 5.23% to the dissimilarity, the red spot monocle bream *S. taeniopterus* (4.34%), the sunrise goatfish *U. sulphureus* (4.23%), the crab *C. truncata* (3.89%) and the Japanese flathead *I. japonica* (3.47%). The goatfish *U. sulphureus* was completely absent from sites in the northern latitudinal group.

Given the marked influence of latitude on the bycatch community structure, a two-way crossed analysis of similarities was undertaken to examine the effects of codend type, with latitude as the first factor and codend type as the second. The latitudinal effect was confirmed (global *R*-statistic = 0.513, $P < 0.001$) but there was no effect of codend type on bycatch assemblages (global *R*-statistic = –0.059, $P = 1.0$), nor was there any evidence of clustering of samples from the MDS due to codend type (Figure 6.4.3C).

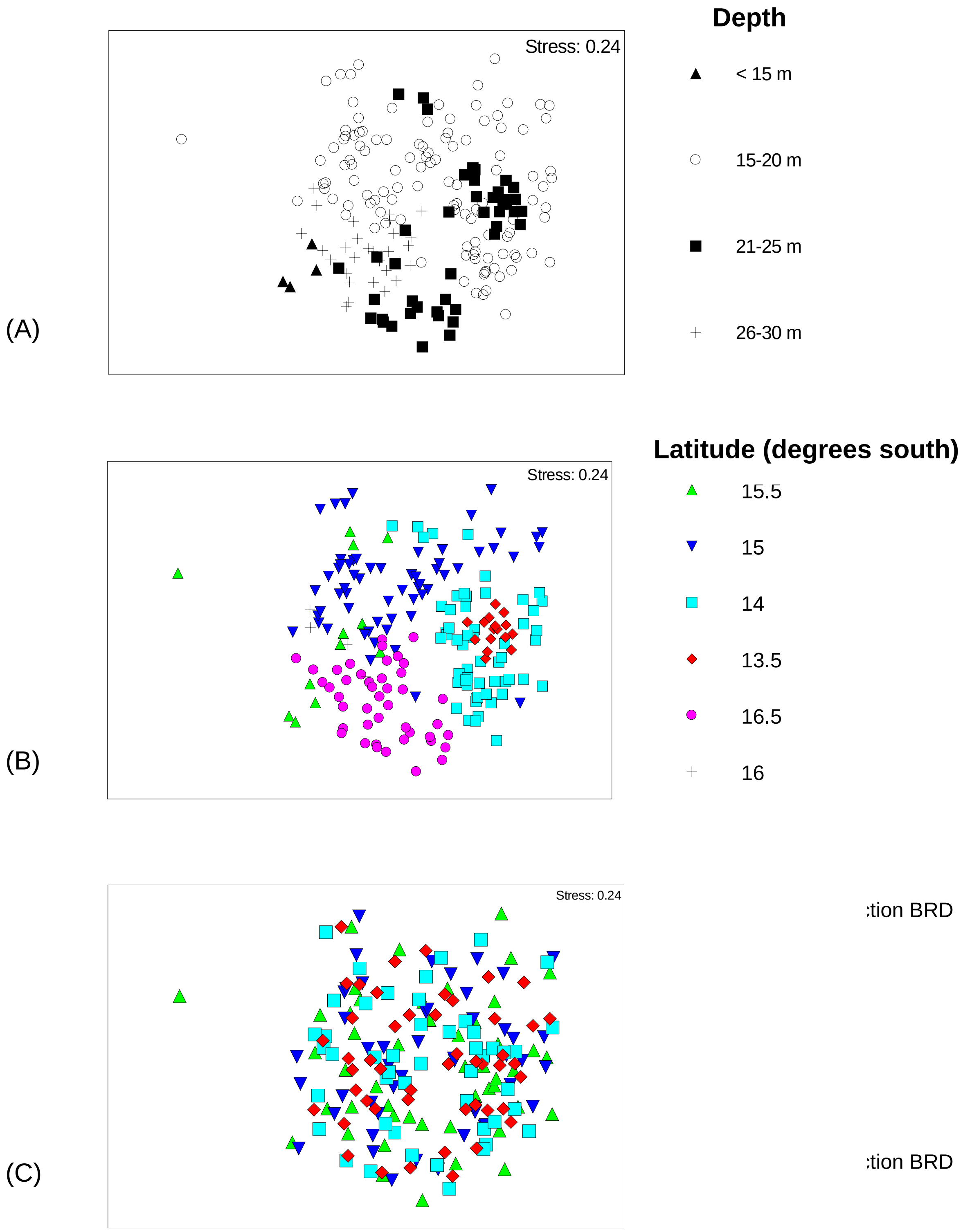


Figure 6.4.3. Two-dimensional MDS of bycatch sub-samples from an experimental research charter undertaken in the north Queensland tiger/endeavour prawn fishery. Catch rates were square-root transformed. The analyses used all 192 sub-samples and 122 species. Note the clustering of bycatch assemblages on (A) depth and (B) latitude, but not on (C) codend type.

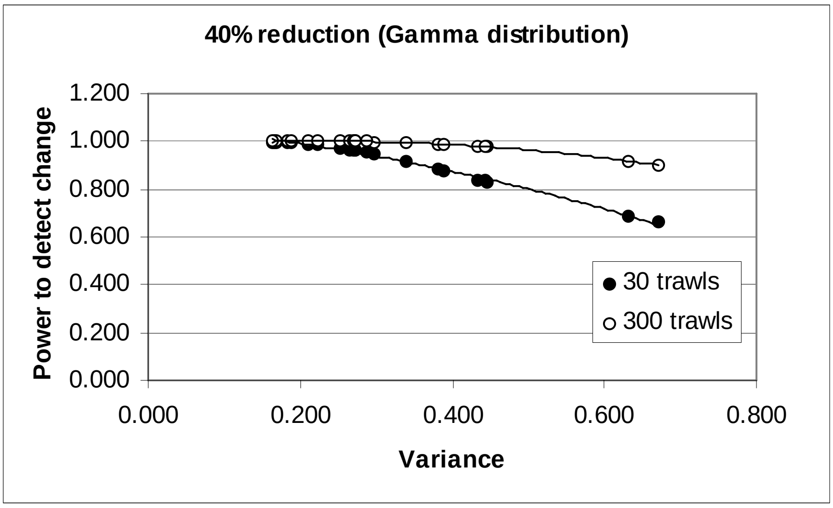
Table 6.4.4. *R*-statistic values and significance levels for differences in bycatch community structure between latitudes. Latitudinal groups are rounded to the nearest half degree.

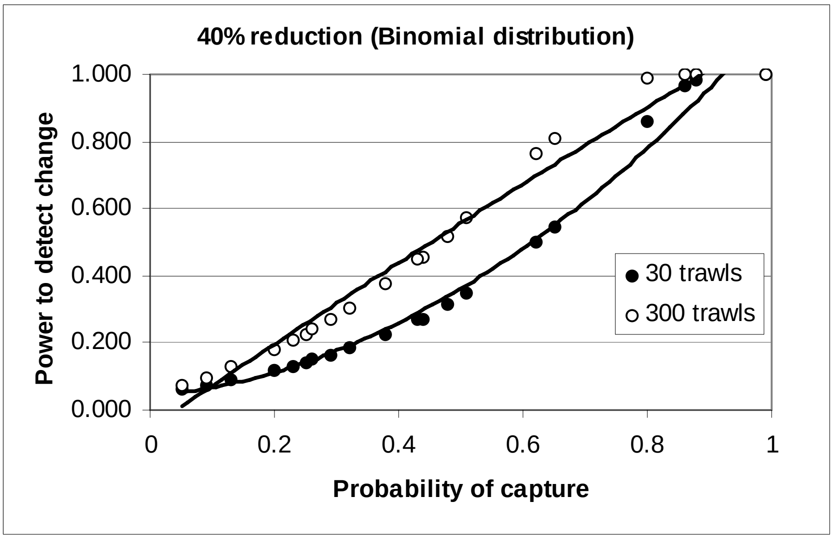
Latitudinal groups	*R*-statistic	Significance level
15.5, 15	0.280	0.001
15.5, 14	0.771	0.001
15.5, 13.5	0.814	0.001
15.5, 16.5	0.622	0.001
15.5, 16	0.367	0.026
15, 14	0.589	0.001
15, 13.5	0.509	0.001
15, 16.5	0.567	0.001
15, 16	0.395	0.002
14, 13.5	-0.015	0.586
14, 16.5	0.595	0.001
14, 16	0.690	0.001
13.5, 16.5	0.795	0.001
13.5, 16	1.000	0.001
16.5, 16	0.144	0.096

6.4.4 Monitoring and the power to detect change in bycatch species catch rates

As expected, power analyses indicated that as the variance in individual species catch rates increased, the power to detect change declined (Figure 6.4.4). For species whose catch rates were best modelled using a gamma distribution (i.e., the majority of species in Table 6.4.2), the variance required to detect a 40% decline in catch rates with a probability of 0.8 or higher would have to be 0.4 or less for a program based on 30 trawl samples. A program based on 300 samples could confidently detect a 40% decline for the entire range of variances considered (i.e., from 0.0 to 0.8). Detecting the larger decline of 80% could be undertaken with absolute confidence (i.e., probability of 1.0) for the range of variances considered (hence, no graph is provided for the 80% reduction scenario).

For those species whose catch rates were best suited to a binomial distribution, the power to detect change increased with increasing probability of capture (Figure 6.4.4). A monitoring program based on 30 trawl samples could detect a 40% decline with a power of at least 0.8 if the probability of capture was 0.8 or higher, while a program based on 300 samples could detect the same change with the same power at a probability of capture of about 0.6 or higher. The probability of detecting an 80% reduction was significantly higher. A monitoring program based on 30 samples could detect an 80% decline with a power of 0.8 if the probability of capture was 0.5 or higher, while a program based on 300 samples could detect the same decline at the same power with a probability of capture as low as 0.3.





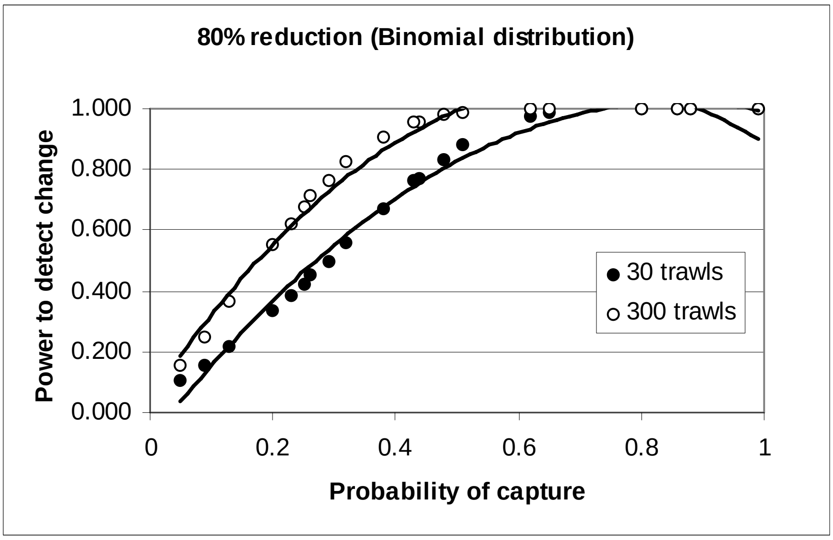


Figure 6.4.4. The power to detect change in bycatch species catch rates in the north Queensland tiger/endeavour prawn fishery for two possible monitoring programs; one based on 30 trawl samples and the other based on 300. The upper graph refers to species' catch rates that conform to a gamma distribution, while the two lower graphs consider catch rate data that are best described as binomial. Two levels of reduction are considered: 40% and 80%.

6.5 DISCUSSION

6.5.1 Evaluating the performance of the TED and radial escape section BRD

The main finding from the charter and subsequent analyses was that when used together, the TED and radial escape section BRD significantly reduced the bycatch rate by 20% ($\boldsymbol{\beta}_3$ parameter estimate of 0.80, Table 6.4.1) without incurring a significant reduction in the catch rate of marketable size prawns. Marketable prawn catch rates were reduced slightly by the TED and radial escape section BRD, but not significantly (Table 6.4.1). The size of the bycatch reduction was similar to, but slightly less than that obtained for the shallow water eastern king prawn charter, where a 24% reduction was achieved using a TED and radial escape section BRD.

Although the results are encouraging, they were slightly disappointing given that the large 200 mm (8-inch) escape meshes were sewn around the entire circumference of the radial escape section, whereas they were restricted to the upper half of the circumference during the shallow water eastern king prawn charter (see Figure 5.3.1). Why then was the reduction in bycatch not as large as that achieved during the shallow water eastern king prawn charter?

One explanation may be due to differences in the composition and length of the bycatch fish species. The dominant bycatch fish species from the shallow water eastern king prawn fishery charter were larger, and therefore possibly stronger swimmers and more capable of escaping through the large escape meshes, than the fish species that comprised the majority of the tiger/endeavour prawn fishery charter bycatch. The incidence of small fish species was higher in the tiger/endeavour prawn fishery charter bycatch. For example, of the fish species that comprised 90% of the bycatch in the standard net, 23% had mean lengths of 70 mm or less, while only 13% from the shallow water eastern king prawn bycatch had mean lengths of 70 mm or less. Small fish species that contributed significantly to the tiger/endeavour prawn fishery bycatch, such as cardinalfish (*A. fasciatus, A. ellioti* and *A. poecilopterus*), ponyfish (*L.* sp. *2* and *L. splendens*) and leatherjackets (*P. otisensis*) were absent from the shallow water eastern king prawn fishery bycatch, possibly because the depths sampled were relatively shallow (i.e., 13.9–27.2 m) compared to the shallow water eastern king prawn charter (i.e., 20.1–90.7 m). All of the fish species that experienced a significant reduction in catch rate due to the radial escape section BRD, or the radial escape section BRD and TED together, had mean standard net lengths larger than 70 mm, with most larger than 100 mm (i.e., *S. taeniopterus, I. japonica, U. sandaicus, T. whitleyi, E. nudiceps, U. tragula* and *L. genivittatus*). Our results suggest that while the radial escape section BRD could be used to significantly reduce bycatch rates in the north Queensland tiger/endeavour prawn fishery, it appears to have little effect for most small (i.e., < 70 mm) fish species, probably because they are incapable of swimming to, and out of, the large escape meshes.

The largest significant reduction in catch rate for any one species was 36% ($\boldsymbol{\beta}_3$ parameter estimate of 0.64, Table 6.4.2) for the naked headed catfish *E. nudiceps,* which had a mean length of 222.53 mm from the standard net (Table 6.4.3) and was the second largest of those species that contributed most to the bycatch. Interestingly, catch rates of the other large fish species that contributed significantly to the bycatch, including the lizardfishes (*S. grandisquamis* and *S. micropectoralis*) and the flatfishes (*P. diplospilus, P. spinosos* and *P. erumei*) were not significantly reduced by the TED or radial escape section, possibly because of their poor swimming ability or morphology.

Another explanation for the lower-than-expected reduction may be due to the speed of the trawls. Mean trawl speeds were 2.3 knots and 3.2 knots for the shallow water eastern king prawn and north Queensland tiger/endeavour prawn charters, respectively. The higher speed, which is characteristic of trawling for tiger prawns, would have created stronger currents in the nets which would have almost certainly lowered the ability of small fish to swim forward and out of the large escape meshes. The codends were also longer (i.e., 100 meshes long) than those used in the shallow water eastern king prawn charter (i.e., 75 meshes long), so not only did the fish have to swim against a stronger current, they also had to swim further to escape.

6.5.2 Variation in bycatch composition

The bycatch was characterised by a) a large number of fish and invertebrate species (317 taxa), most of which were uncommon (73% occurred in fewer than 10% of sub-samples), b) dominant species groups (by weight) were flatfish, nemipterids, cardinalfish, lizardfish, catfish, dragonets, leatherjackets, toadfish, ponyfish, goatfish and invertebrates including non-targeted penaeid prawns and portunid crabs, and c) faunal community assemblages that varied significantly with latitude and to a lesser degree depth (Figure 6.4.3A,B). Although the bycatch rate was significantly reduced by using the TED and radial escape section BRD, the MDS analysis suggests that the devices are unlikely to alter the general composition of the bycatch or result in distinct “non-BRD” or “BRD” assemblages.

Watson et al. (1990) described the demersal trawl-caught fauna on the Queensland coast between 18^{o}30’ S and 20^{o} S, which is south of the region examined in the present study. They sampled over a broader range of depths (17–56 m) and further offshore to include inter-reefal areas. The dominant species groups were very similar to those reported herein, and included the flatfishes, leatherjackets, goatfish and nemipterids, as well as the penaeid and portunid crustaceans. Possibly the most notable difference was the abundance of the sea urchin *Maretia planulata,* which they reported as “discontinuously very numerous and sometimes dominated the trawl catch”. This species was not recorded in the present study, possibly because it is associated with reefal sites outside of the area sampled.

When compared to the shallow water eastern king prawn fishery charter, overall mean bycatch rates were low (4.08 kg ha^{-1} for tiger/endeavour compared to 9.56 kg ha^{-1} for shallow eastern king) while catch rates for marketable prawns were similar (0.80 kg ha^{-1} for tiger/endeavour compared to 0.94 kg ha^{-1}). Interestingly, the weight and numbers of elasmobranchs were also low compared to the shallow water eastern king prawn charter. For example, 409 elasmobranchs were caught during the shallow water eastern king prawn charter while only eight were caught in the present charter (i.e., a 50-fold difference in catch rate), and yet the total area swept by the sampling gears was similar (i.e. approximately 427 ha for the shallow water eastern king prawn charter and 364 ha for the tiger/endeavour prawn charter). The relatively low bycatch rates are particularly interesting given that the sites trawled were relatively shallow (13.9 to 27.2 m) and from the relationship between depth and bycatch rates (Figure 5.4.2 in the previous chapter) relatively high bycatch rates in the order of 10^{-}15 kg ha^{-1} might have been expected. An overall mean of 4.08 kg ha^{-1} is therefore low and possibly indicative of impacts from trawling. Alternatively, it may simply imply that the demersal faunal productivity and standing biomass are higher in the shallow water eastern king prawn fishery than in the north Queensland tiger/endeavour prawn fishery.

6.5.3 Monitoring bycatch species catch rates

The study provided information on the mean catch rates and variance for 317 taxa in the north Queensland tiger/endeavour prawn fishery bycatch that can be used to design a bycatch monitoring program, should it be required. Power analyses (Figure 6.4.4) showed that the probability of detecting change in species catch rates declined as a) the variance of the catch rates increased for gamma distributed species, and b) as the probability of capture declined for binomially distributed species. In general, a 30-sample monitoring program would require the variance to be less than about 0.4 to detect a 40% reduction in catch rate. While this is achievable for many of the commonly encountered bycatch species, it may not be applicable for the less common, or rare species. The variance would not have to be this low if only large changes (i.e., 80%) were to be monitored. For binomially distributed species, probabilities of capture would have to be high, around 0.8, to detect a 40% reduction based on a 30-sample program and a power of 0.8. Since only 13 species were present in more 80% or more of the sub-samples (Table 6.4.3), only very few species could be adequately modelled using this approach. Predictably, all of these results suggest that a 300-sample monitoring program would more confidently detect both large and small changes in bycatch species catch rates than a smaller 30-sample program, but at significantly greater operational costs.

6.6 REFERENCES

Jones, C.M., Derbyshire, K., 1988. Sampling the demersal fauna from a commercial penaeid prawn fishery off the central Queensland coast. Mem. Queensl. Mus. 25, 403-415.

Montgomery, D.C., 1997. Design and Analysis of Experiments, 4th ed. John Wiley and Sons.

O'Neill, M. F., Courtney, A. J., Turnbull, C.T., Good, N. M., Yeomans, K. M., Staunton Smith, J., Shootingstar, C., 2003. Comparison of relative fishing power between different sectors of the Queensland trawl fishery, Australia. Fish. Res. 65: 309-321.

Robins, J., Eayrs, S., Campbell, M., Day, G., McGilvray, J., 2000. Commercialisation of bycatch reduction strategies and devices within northern Australian prawn trawl fisheries. FRDC Project Number 96/254, p. 40.

Snedecor, G.W., Cochran, W.G., 1967. Statistical Methods, 6th ed. The Iowa State University Press, Ames, Iowa, USA.

Sterling, D., 2000. The Physical Performance of Prawn Trawling Otter Boards and Low Opening Systems. Brisbane, DJ Sterling Trawl Gear Services.

Watson, R.A., Dredge, M.L.C., Mayer, D.G., 1990. Spatial and seasonal variation in demersal trawl fauna associated with a prawn fishery on the central Great Barrier Reef, Australia. Aust. J. Mar. Freshw. Res. 41, 65-77.

Watson, R.A., Goeden, G., 1989. Temporal and spatial zonation of the demersal trawl fauna of the central Great Barrier Reef. Mem. Queensl. Mus. 27, 611-620.

7 Round scallops and square meshes: effects of bycatch reduction devices in the Queensland (Australia) scallop trawl fishery

A. J. Courtney, M. J. Campbell, D. P. Roy, M. L. Tonks, K. E. Chilcott and P. M. Kyne

7.1 ABSTRACT

This chapter presents results from an eight-day research charter that was designed to quantify the effects of a turtle excluder device (TED) and a square mesh codend bycatch reduction device (BRD) on bycatch and saucer scallop catch rates in the Queensland scallop fishery. A total of 382 taxa were recorded from 236 bycatch sub-samples. Approximately 64% of the weight of the bycatch was attributed to large bycatch fauna, of which sponges (Porifera) comprised 92%. The remaining 8% of large fauna were comprised of a relatively few large sharks and rays, croakers and lutjanids. The dominant species groups that comprised the remaining 36% of the bycatch were lethrinids, portunid crabs, scorpinids, nemipterids, lizardfish, leatherjackets, flatfish, pufferfish, holothurians, bryozoans and sea urchins. When the TED and square mesh codend BRD were both installed in the codend the total mean bycatch rate (i.e., including large fauna) was reduced significantly by 77%, with no significant effect on the mean catch rate of legal size (i.e., > 95 mm shell height) scallops and 63% fewer undersize scallops, compared to a standard net with no TED or BRD. Several bycatch species experienced extremely high reductions in mean catch rate when both devices were installed, including *Lethrinus genivittatus* (96% reduction), the red portunid crab *Portunus rubromarginatus* (88% reduction), the dusky leatherjacket (86% reduction) and threadfin bream *Nemipterus theodorei* (85% reduction), mainly due to the square mesh codend BRD. Multidimensional scaling and analysis of similarities revealed that the bycatch assemblages differed significantly between depth, latitude and codend treatment type. We recommend that square mesh codends be used in the Queensland saucer scallop fishery as a means of reducing bycatch and improving the size selectivity of the scallops.

7.2 INTRODUCTION

Concern over the amount of bycatch discarded from commercial fisheries, and research into the problem, have increased globally over the last decade (Alverson et al., 1994; Broadhurst, 2000; Hall et al., 2000; Hall and Mainprize, 2005). The Queensland East Coast Trawl Fishery (QECTF) has the largest benthic trawl fleet in Australia and as such the amount of bycatch produced annually is substantial. In the late 1990s it was estimated to exceed 25,000 t annually (Robins and Courtney, 1998). Bycatch and other impacts from the fishery are particularly contentious as about 70% of the fishery’s catch and effort occur in the Great Barrier Reef Marine Park.

In 2004 the fishery consisted of approximately 500 licensed trawlers that were allocated approximately 80,000 boat-nights of fishing effort. The fishery targets penaeid prawns (*Penaeus* spp. and *Metapenaeus* spp.) and saucer scallops (*Amusium japonicum ballotti*) but fishers can also retain incidental catches of several other species (i.e., byproduct) including blue swimmer crabs (*Portunus pelagicus*), scyllarid lobsters (*Thenus* spp. and *Ibacus* spp.), barking crayfish (*Linuparus trigonus*), squid, cuttlefish, octopus, mantis shrimps and select species of finfish. Approximately

10,000 t of seafood is marketed annually from the fishery valued between A$101 and 132 million (Kerrigan et al., 2004).

Between 1999 and 2002, in response to mounting pressure to reduce bycatch, the Queensland Government passed a mandatory regulation that required fishers to install both a turtle excluder device (TED) and a bycatch reduction device (BRD) in every otter trawl net, with the exception of small try-gear nets. TEDs were introduced specifically to reduce the incidental capture of turtles but have also been shown to reduce bycatch of other large fauna, including sharks, rays and sponges (Brewer et al., 1998). At the time of writing, the fishery's Management Plan listed seven recognised BRDs that fishers can choose from.

The saucer scallop (*Amusium japonicum ballotti*) fishery is a commercially important sector within the QECTF. From 1989 to 1996 the average annual reported weight of scallop meat was 962 t (O'Neill et al., 2005). Annual levels of scallop fishing effort were relatively stable between 1990 and 2001, averaging about 13,583 boat-nights per year, but have declined in recent years in response to management changes. While there is no specific license requirement (i.e., all 490 operators can trawl for scallops), management measures for the scallop fishery include a) the use of rotational spawning stock closures, b) seasonally changing minimum legal sizes, and c) a minimum mesh size of 75 mm, which fishers apply to conventional diamond mesh nets.

There is scant information on the amount and composition of bycatch in the scallop fishery, although fishery-independent surveys (Dichmont et al., 2000; Barker et al., 2004) indicate the bycatch weight exceeds that of the reported scallop meat weight by several fold. Most scallop fisheries use benthic dredges and as such their bycatch is dominated by epibenthic invertebrates (Currie and Parry, 1994; DuPaul et al., 1996; Veale et al., 2001; Bremec and Lasta, 2002), but because the Queensland fishery uses otter trawls the composition of the bycatch may be considered atypical. DuPaul et al., (1996) identified modifications to scallop dredge gear for reducing bycatch of finfish, undersized scallops and damage to bycatch species, but these approaches are not applicable to otter trawl gear.

One approach that may be suitable for reducing bycatch in the Queensland scallop fishery is the square mesh codends. These are codends constructed largely of meshes that are hung on the bar resulting in a matrix of squares that remain open, thus allowing small bycatch species to escape (Eayrs et al., 1997). Conventional diamond meshes close up when stretched or under load, greatly reducing escapement. Square mesh codends have been shown to reduce bycatch in several fish- and crustacean-trawl fisheries with minimal or no loss of the targeted catch (Suuronen and Millar, 1992; Thorsteinsson, 1992; Broadhurst et al., 1999; 2004). They can also improve the selectivity of the target species by lowering the retention of undersized individuals. Square mesh codends appear to have potential in the scallop fishery as a means of reducing bycatch because a) much of the bycatch is comprised of relatively small finfish and invertebrates that could escape through the square meshes and b) provided the squares are smaller than the minimum legal size of the scallops, there should be minimal loss of targeted catch. Another attractive feature of square mesh codends is that, unlike most other BRDs that rely on bycatch being able to locate the escapement hole and then swim through it, square mesh codends provide "multiple points of escapement", which many species can either passively pass through, or even simply fall through.

The objective of this chapter was to evaluate the square mesh codend as a BRD in the Queensland scallop fishery. Because all trawlers in Queensland must now have a TED as well as a BRD in every net, the study quantified the effects of the square mesh codend with, and without a TED. Several hypotheses were tested in the study but the central null hypothesis was that the square mesh codend had no significant effect on the catch rate of bycatch or scallops, compared to the standard diamond-mesh nets used by the fleet.

7.3 METHODS

7.3.1 Research charter design

The effects of the square mesh codend were evaluated during a purposely designed eight-night research charter in October 2002 in the scallop fishery. To ensure the bycatch composition and scallop catch rates were similar to those of the fleet, all trawl sampling was conducted in areas that received medium to high levels of trawl fishing effort for the months of October–December, based on logbook data from 1996 to 2001. The distribution of sample sites was stratified so that areas that received high levels of effort received more sampling than medium-effort areas. The commercial trawler *Southern Intruder* and her crew, who allocate a significant proportion of their annual fishing effort in the scallop fishery, were hired to undertake the charter, in conjunction with project research staff on board.

In the scallop fishery most vessels tow either three nets (i.e., one net on both the port and starboard sides and a third net from the stern; referred to as triple gear) or four nets (two nets towed on each of the port and starboard sides, referred to as quad gear) (O'Neill et al., 2005). Quad gear was preferred for research purposes because it facilitated comparison of more (i.e., four) codend types simultaneously at each site. The four codend types were:

- 88 mm (3½ inch) standard diamond mesh codend with no TED and no BRD (referred to throughout as the "standard codend");
- 88 mm (3½ inch) standard diamond mesh codend with TED;
- 100 mm (4 inch) square mesh codend BRD; and
- 100 mm (4 inch) square mesh codend BRD with TED.

The codends were sewn onto new six-fathom, two-seam Florida Flyer nets with standard diamond mesh. This type of net is commonly used throughout the fishery and new nets were deployed to minimise between-net variation that may have been due to wearing, stretching or repairs.

The standard 88 mm mesh codend was 33 meshes long, 60 meshes round and constructed from 6 mm braided polyethylene (Figure 7.3.1). The 100 mm square mesh codend BRD was also constructed of 6 mm braided polyethylene, 36 bars round and 40 bars long. When hung on the bar it produced a matrix of open square meshes that were 50 mm by 50 mm (Figure 7.3.2). A short section of diamond mesh, 60 meshes round and 5 meshes long, constructed from the same material as that used in the square mesh codend BRD, was sewn onto the forward end to attach lifting points for the retrieval lines. Another short section of the 88 mm diamond mesh, 36 meshes round and 3 meshes long, was sewn onto the aft end so that the drawstring could be attached. Four lengths of 12 mm polyethylene rope were selvedged along four sides of the square mesh codend BRD to take the weight of the accumulated catch, thereby reducing mesh distortion and knot slippage. The standard 88 mm mesh codend and the 100 mm square mesh codend had the same total lengths. Rubber chafing mats were attached to all codends. The TED used throughout the charter was a solid grid constructed from 25 mm (1 inch) aluminium tubing, 800 mm wide, 1080 mm high, with a bar space of 120 mm and sewn into a codend extension at 60^o in top-shooter mode (Figure 7.3.1). The deflector bars were bent by 30^o approximately 150 mm (6 inches) from the top of the grid.

At each site the four nets were towed simultaneously along the bottom for precisely two nautical miles (3704 m), measured using a global positioning system. The nets were towed in a straight line so that each swept the same size area along the bottom. Given the spatial distribution of the fishery, “steaming” time between sites, and the time required to winch away, retrieve nets and process the catch, it was estimated that seven to eight sites could be trawled each night (note the scallop fishery is fished at night and daylight trawling is prohibited).

7.3.2 Sampling the catch

After each site was trawled all four nets were retrieved and their codends emptied onto a partitioned sorting tray to keep their contents separated. The following procedure was applied to the catch of each net. Large bycatch species (i.e., weighing more than about 10 kg) and species of conservation interest that could not be retained were identified, weighed, recorded and released. These species included turtles, large sharks, rays, pufferfish and sponges and were collectively referred to as “large bycatch fauna”. The scallop catch was weighed and recorded, and with the exception of large catches (i.e., > 10 kg), all scallops were retained, labelled, frozen and later processed in the laboratory. When large catches of scallops were obtained a sub-sample of about 10 kg was retained, labelled, frozen and later processed in the laboratory. Moreton Bay bugs (*Thenus orientalis*) are a valuable byproduct in the scallop fishery and were removed from the catch, labelled, frozen and later processed in the laboratory. (Note: Moreton Bay bugs are defined in the Management Plan as a principal target species and can therefore be targeted, so strictly speaking, they are not byproduct). The remaining bycatch was placed in plastic baskets, weighed to the nearest 0.1 kg and recorded. A 10 kg (approximate) sub-sample of the bycatch was then obtained by scooping it into a labelled cardboard carton, frozen on board and later processed in the laboratory. If the bycatch was less than approximately 10 kg then it was retained in its entirety.

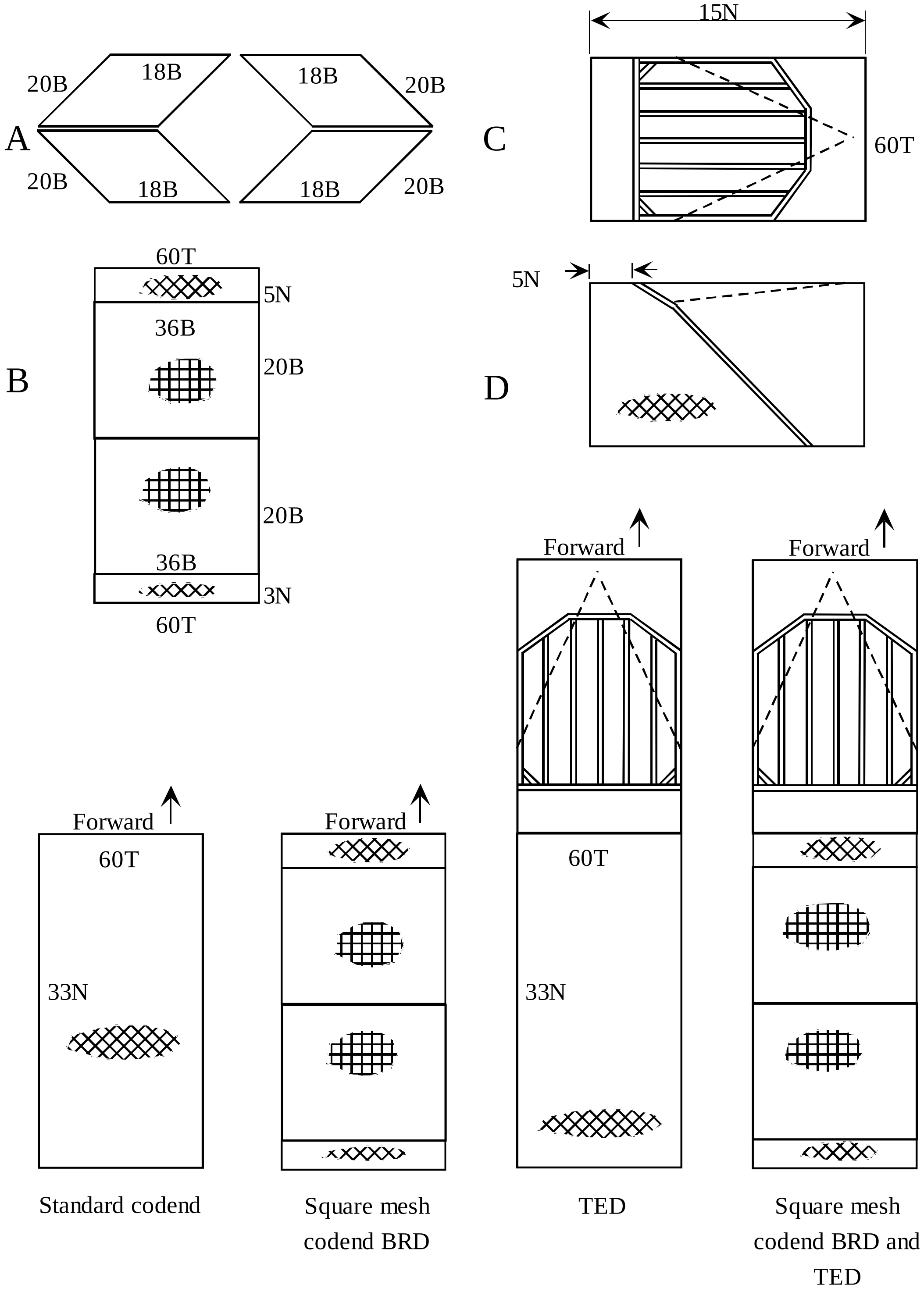


Figure 7.3.1. A – The square mesh codend was constructed using four identical pieces of 4-inch (100 mm), 6 mm polyethylene mesh. Each piece of mesh was 18 bars wide and 20 bars long and, sewn together, resulted in a single tube of mesh 36 bars round by 40 bars long. B – Plan view of the square mesh codend BRD. A small length of diamond mesh was sewn on the aft edge of the square mesh codend to facilitate the addition of drawstrings. Similarly, a section of diamond mesh was added to the forward edge of the square mesh codend to allow the codend to be sewn onto the nets used during the charter. C – Plan view of the TED. D – Elevation of the TED.

Figure 7.3.2. The square mesh codend BRD under construction. Note the large open squares (50 mm x 50 mm). The 12 mm polyethylene rope was selvedged along the sides to take the weight of the bycatch and prevent distortion of the mesh.

7.3.3 In the laboratory

In the laboratory the weight and shell height of every scallop were measured to the nearest 0.1 g and 0.1 mm, respectively, and recorded. The scyllarid lobsters were measured to the nearest 0.1 mm carapace width (CW). Each individual in the bycatch sub-samples was identified to species level, counted and the total weight of each species recorded. Length measures for the bycatch species (standard length or total length for fish, carapace length or width for crustaceans, disc width or length for elasmobranchs, total length for echinoderms and shell length for molluscs) were obtained from a maximum of 20 individuals of each species from each sub-sample. The precise total weight of each sub-sample was determined by summing the individual species weights contained within it.

7.3.4 Calculating catch rates of scallops and bycatch species

Methods for estimating catch (in weight, kg or g) per swept area trawled (hectares, ha) were similar to those described in Chapter 5, section 5.3.4. The area swept *S* by net *n* during trawl *t* was estimated thus:

$$S_{tn} = \frac{H \times F \times D}{10{,}000}$$

where *H* was the headline length of the net (6 fm net head rope length equates to 10.97 m), *F* was the net spread factor for quad gear (0.70) from Sterling (2005) and *D* was the distance trawled (2 nautical miles = 3704 m). Division by 10,000 converts the area from square metres to hectares.

7.3.5 Statistical design and analyses

Statistical methods for determining effects due to a) trawl site, b) codend treatment type, and c) net position were the same as those described in Chapter 5, section 5.3.5.

The codends were sampled in four net positions (port inner net, port outer net, starboard inner net and starboard outer net) and to take account of any effects due to net position, the net position of each codend type was recorded and considered in the analyses. In order to subject each codend type to each net position, the codends were cut off the nets after each night of sampling and sewn on in another net position. The net position that each codend was allocated to was randomised, followed a pre-determined protocol (Table 7.3.1) and designed so that each codend type was sampled in each net position on two nights.

Table 7.3.1. The sampling protocol for codend type and net position applied during the charter. The number of sites trawled each night is shown in brackets.

	Net position			
Night of sampling	**Port inner net**	**Port outer net**	**Starboard inner net**	**Starboard outer net**
1 (7)	TED	Square mesh codend BRD with TED	Standard codend	Square mesh codend BRD
2 (8)	Standard codend	Square mesh codend BRD	TED	Square mesh codend BRD with TED
3 (6)	Square mesh codend BRD with TED	TED	Square mesh codend BRD	Standard codend
4 (8)	Square mesh codend BRD	Standard codend	Square mesh codend BRD with TED	TED
5 (7)	TED	Standard codend	Square mesh codend BRD	Square mesh codend BRD with TED
6 (9)	Standard codend	TED	Square mesh codend BRD with TED	Square mesh codend BRD
7 (7)	Square mesh codend BRD	Square mesh codend BRD with TED	TED	Standard codend
8 (7)	Square mesh codend BRD with TED	Square mesh codend BRD	Standard codend	TED

Because all four codend types were sampled at each site simultaneously a complete block design (Montgomery, 1997) was applied, with site as a blocking term. Generalised linear modelling (GLM) using GenStat (2005) statistical software was used to examine the variation in catch rates of bycatch (both total bycatch and individual bycatch species) and scallops, and variation in the mean length of bycatch species. Model distributions and link functions included a) normal distribution with identity link, b) binomial distribution with logit link, c) Poisson distribution with logarithm link, and d) gamma distribution with logarithm link functions. Three data transformations were trialled when normal distributions were used: power, log and square root. The best model goodness-of-fit was obtained by examining plots of the standardised residuals and if residuals were not normally distributed then the model distribution type or transformation would be changed until normality was attained. The models took the following general form:

$$U = \beta_o + \beta_1(\text{Trawl site}_{1-n}) + \beta_2(\text{Net position}_{1-4}) + \beta_3(\text{Codend type}_{1-4}) + \varepsilon$$

where U was the predicted mean catch rate of bycatch weight, individual bycatch species weight or scallop weight, or length of a bycatch species, n was the number of sites trawled, $\boldsymbol{\beta}_o$ and $\boldsymbol{\beta}_2$ were scalar parameters that were estimated, and $\boldsymbol{\beta}_1$ and $\boldsymbol{\beta}_3$ were vector parameters that were estimated and ε was the error term. Only estimates of $\boldsymbol{\beta}_3$ are presented as this parameter quantifies the effects of the different codend types. For purposes of interpretation, the $\boldsymbol{\beta}_3$ parameter estimates were proportionally scaled so that they could be compared against a standard codend parameter value of 1.0.

Multidimensional scaling (MDS) was used to examine variation in the bycatch community structure due to latitude, depth and codend type. The statistical software package PRIMER (Plymouth Routines in Multivariate Ecological Research) by Clarke and Warrick (1994), was used to undertake the analyses, following the same procedures as described in Chapter 5, section 5.3.5. To reduce the number of factor levels, depths were rounded to the nearest 10 m and latitude to the nearest 0.5 degree. Again, MDS was carried out on species that were present in at least 5% of samples to avoid the species-sample matrix table from being dominated by zeros.

7.4 RESULTS

A total of 59 sites were trawled (Figure 7.4.1) over the eight nights resulting in 236 (i.e., 59 sites x 4 nets) measurements and sub-samples of bycatch and scallops. The number of sites sampled each night is provided in Table 7.3.1. The average speed and duration of each trawl were 2.3 knots and 53 minutes, respectively. The total weight of bycatch (i.e., including large bycatch fauna) and scallops (including all size classes) were 6212.4 kg and 1333.1 kg respectively, with 382 taxa identified in the bycatch. Approximately 64% of the bycatch weight was attributed to large bycatch fauna, of which large sponges (Porifera) comprised 92%. The remaining 8% was attributed to a small number of relatively large sharks, rays, croakers, lutjanids and pufferfish and included the eastern shovelnose ray (*Aptychotrema rostrata*), leopard whipray (*Himantura undulata*), blue-spotted stingray, (*Dasyatis kuhlii*), whitespotted wedgefish (*Rhynchobatus australiae*) and starry pufferfish (*Arothron stellatus*).

The remaining 36% of the bycatch was comprised of small species of fish and invertebrates, calcareous rubble and seagrass. Of these, eight species accounted for 50% of the weight: the longspine emperor (*Lethrinus genivittatus* 12%), red portunid crab (*Portunus rubromarginatus* 7%), undersized blue swimmer crabs (*Portunus pelagicus* 7%), the Caledonian stinger (*Inimicus caledonicus* 6%), threadfin bream (*Nemipterus theodorei* 5%), the lizardfish (*Saurida grandisquamis* 5%), the many-striped pufferfish (*Anchisomus multistriatus* 4%) and the sponge (*Callyspongia* sp. 4%). Forty-nine taxa accounted for 90% of the weight. A complete list of 488 taxa that the project recorded from the scallop fishery bycatch, and their catch rates, is provided in Appendix 3. It includes the 382 species recorded from the scallop research charter and additional species that were recorded in opportunistic samples obtained from commercial vessels operating in the scallop fishery.

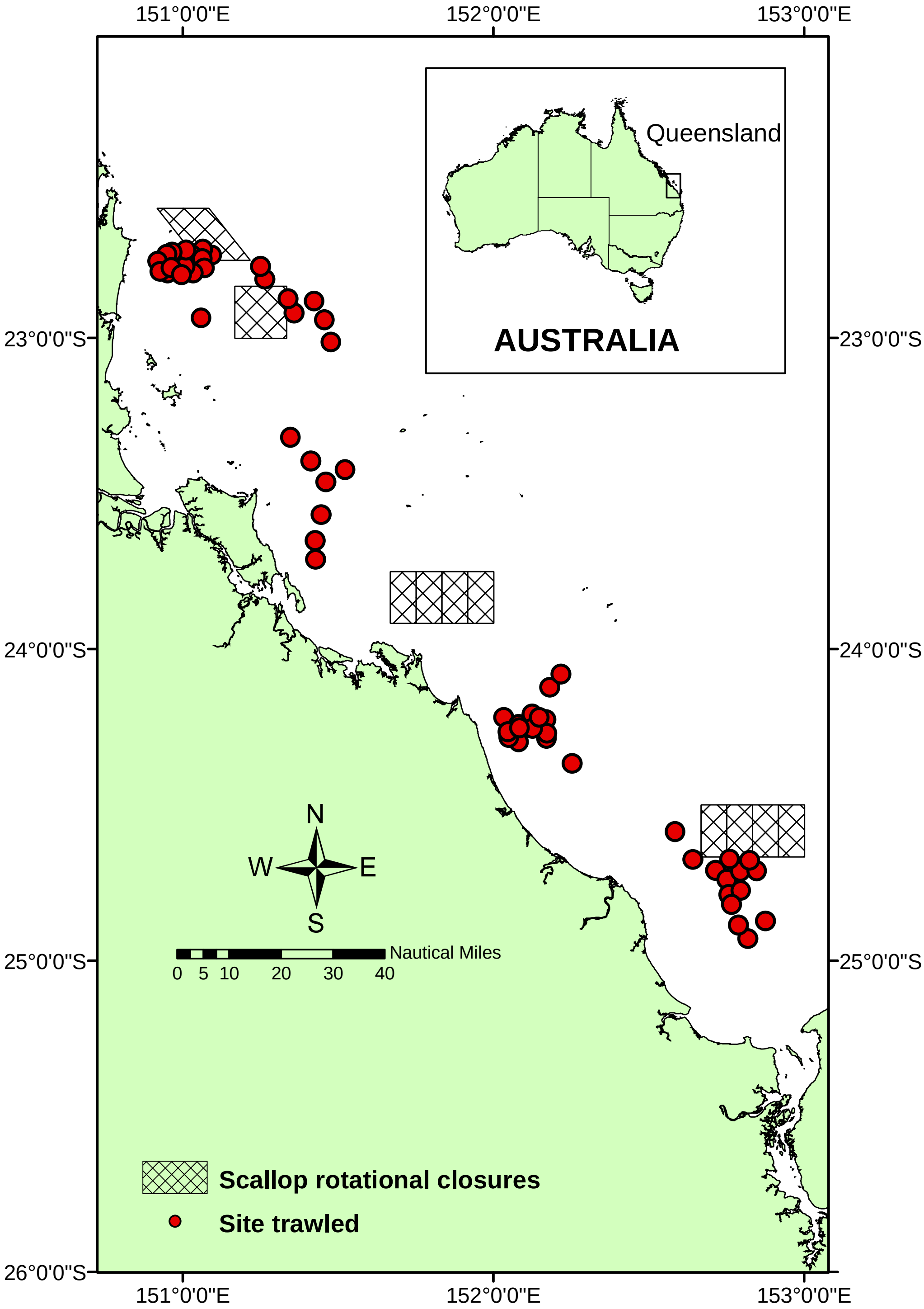


Figure 7.4.1. Location of the 59 sites trawled during the charter in the Queensland scallop fishing grounds. At each location four nets were towed, each with a different type of codend, resulting in 236 measurements of bycatch and scallop catch rates.

7.4.1 *Effects of codend type on bycatch and scallops*

The effects of codend type on bycatch catch rates were modelled using two response variables. The first was total bycatch weight and included the large bycatch fauna. The second was bycatch weight excluding large bycatch fauna; this was undertaken to examine the effects with large sponges removed. The observed mean catch rate for total bycatch from the standard net was 15.89 kg ha^{-1}. The TED by itself reduced the catch rate of total bycatch by 47% ($\boldsymbol{\beta}_3$ parameter estimate of 0.53, Table 7.4.1) compared to the standard codend. The square mesh codend by itself reduced the total bycatch catch rate by 40% ($\boldsymbol{\beta}_3$ parameter estimate of 0.60, Table 7.4.1). When both devices were used together they reduced total bycatch catch rate by 77% ($\boldsymbol{\beta}_3$ parameter estimate of 0.23, Table 7.4.1). All reductions were significantly ($P < 0.05$) less than that of the standard codend.

Table 7.4.1. Effects of codend type on the catch rates of bycatch and scallops based on 236 measures of bycatch and scallop catches (59 sites trawled x 4 nets). Generalised linear modelling was used to quantify the effects. Significant differences between codends ($P < 0.05$) are bolded and identified by different alphabetic characters (A, B, C or D). Parameter estimates were proportionally scaled so they can be compared to a standard net parameter value of 1. Standard errors in parentheses.

Catch component	**Mean observed catch rate (kg ha^{-1}) Standard net codend**	**Predicted change in catch rates based on generalised linear model parameter estimates (proportionally scaled to a Standard net parameter value of 1)**			**Distribution type**
		TED only	**Square mesh codend BRD only**	**Square mesh codend BRD and TED together**	
Total Bycatch	**15.89 (2.48) A**	**0.53 (0.07) B**	**0.60 (0.08) B**	**0.23 (0.03) C**	**Gamma**
Bycatch excluding large fauna	**4.59 (0.48) A**	**1.11 (0.11) A**	**0.44 (0.04) B**	**0.46 (0.05) B**	**Gamma**
Legal sized scallops	**1.03 (0.19) A**	**0.97 (0.09) A**	**1.12 (0.11) A**	**1.03 (0.10) A**	**Normal (log transformed)**
Undersized Scallops	**0.53 (0.09) A**	**0.95 (0.02) AB**	**0.85 (0.02) B**	**0.68 (0.02) C**	**Normal (square-root transformed)**

The observed mean catch rate from the standard net for the bycatch, excluding the large fauna, was 4.59 kg ha^{-1} (Table 7.4.1). The TED by itself had no significant effect on the bycatch excluding large fauna, but catch rates fell significantly in nets with the square mesh codends. A 56% reduction was obtained in the net with the square mesh codend by itself ($\boldsymbol{\beta}_3$ parameter estimate of 0.44, Table 7.4.1) and the codend with both the TED and square mesh codend produced a 54% reduction ($\boldsymbol{\beta}_3$ parameter estimate of 0.46, Table 7.4.1). The results suggest that the TED is effective at reducing large species and that the square mesh codend is effective at reducing smaller species, and when used together the devices effectively excluded the majority of the bycatch.

None of the codend types had a significant effect on the legal size (≥ 95 mm shell height) scallop catch rates (Table 7.4.1). However, catch rates of undersized scallops fell significantly in nets with the square mesh codend. The TED by itself had no significant effect on undersize scallop catch rates (β_3 parameter estimate of 0.95, Table 7.4.1). The square mesh codend by itself reduced catch rates by 15% (β_3 parameter estimate of 0.85, Table 7.4.1) and when the TED and square mesh codend were used together they produced a 32% reduction (β_3 parameter estimate of 0.68, Table 7.4.1) compared to the standard net. Because many of the undersized scallops were small (i.e., 40–80 mm shell height, Figure 7.4.2), relatively small reductions in catch weight can equate to large reductions in number. When the number of scallops caught in the nets was examined there were 63% fewer undersized scallops in the net with the TED and square mesh codend compared to the standard codend (Figure 7.4.2

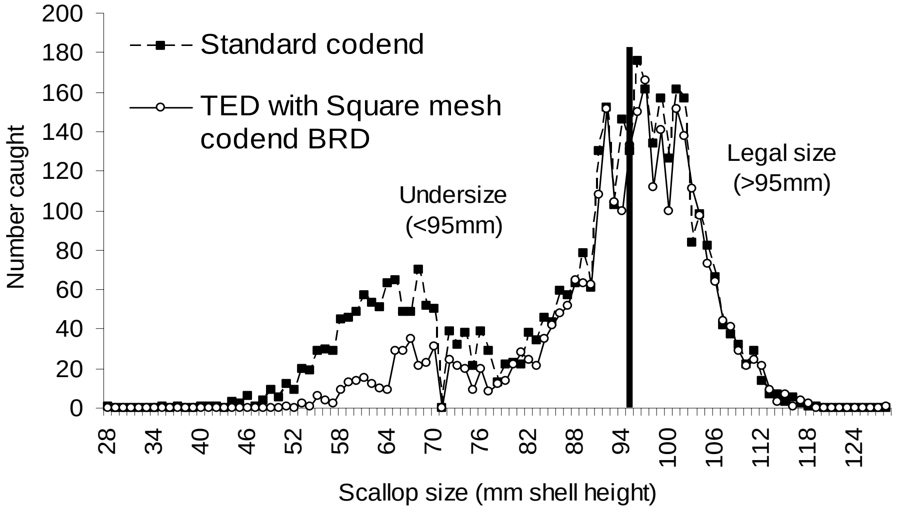


Figure 7.4.2. Size-frequency distribution scallops from the standard codend and from the net with the TED and square mesh codend.

7.4.2 *Effects of codend type on Moreton Bay bugs*

Because there were relatively few lobsters caught in each net at each site, the data were analysed using numbers rather than catch weight, and consequently a Poisson distribution, which is more appropriate for count data, was applied in the GLM. Two analyses were undertaken; one for legal sized (≥ 75 mm CW) lobsters and one for undersized. The mean observed catch rate of legal sized lobsters in the standard codend was 2.93 ha^{-1} (Table 7.4.2). When the TED and square mesh codend were used together the catch rate was reduced by 28% (β_3 parameter estimate of 0.72, Table 7.4.2). The TED by itself reduced the catch rate by 21% (β_3 parameter estimate of 0.79, Table 7.4.2) and the square mesh codend by itself reduced the catch rate by 20% (β_3 parameter estimate of 0.80, Table 7.4.2). Catch rates from all three codend types were significantly ($P < 0.05$) lower than that of the standard codend.

The observed mean catch rate of undersized lobsters from the standard codend was 1.02 ha^{-1} (Table 7.4.2). While the TED reduced the catch rate of undersized lobsters by 18% (β_3 parameter estimate of 0.82, Table 7.4.2), much larger reductions were achieved with the square mesh codends. For example, the square mesh codend by itself reduced the catch rate by 74% ($\boldsymbol{\beta}_3$ parameter estimate of 0.26, Table 7.4.2) and the TED and square mesh codend together reduced the catch rate by 76% ($\boldsymbol{\beta}_3$ parameter estimate of 0.24, Table 7.4.2).

Table 7.4.2. Effects of codend type on the catch rates of Scyllarid lobster (*T. orientalis*) byproduct based on 236 measures (59 sites trawled x 4 nets). Generalised linear modelling was used to quantify the effects. Significant differences between codends ($P < 0.05$) are bolded and identified by different alphabetic characters (A, B, C or D). Parameter estimates were proportionally scaled so they could be compared to a standard net parameter value of 1. Standard errors in parentheses.

Catch Component	**Mean observed catch rate (number caught ha^{-1}) Standard Net codend**	**Predicted change in catch rates based on generalised linear model parameter estimates (proportionally scaled to a Standard net parameter value of 1)**			**Distribution type**
		TED only	**Square mesh codend BRD only**	**Square mesh codend and TED together**	
Legal size lobsters (>= 75 mm CW)	**2.93 (0.22) A**	**0.79 (0.09) B**	**0.80 (0.09) B**	**0.72 (0.08) B**	**Poisson**
Undersized lobsters (< 75 mm CW)	**1.02 (0.16) A**	**0.82 (0.20) B**	**0.26 (0.08) C**	**0.24 (0.08) C**	**Poisson**

7.4.3 Effects of codend type on bycatch species

Because most species were relatively uncommon (i.e., 90% of species were present in fewer than 14% of the 236 samples), resulting in high zero counts, it was not possible to quantify the effects for the majority of species. Analyses were undertaken on 49 taxonomic groups or species that comprised 90% of the weight of the bycatch (excluding sponges but including other large fauna such as sharks and rays) in the standard codend (Table 7.4.3). Statistically significant reductions were detected for 26 species (53%) due to the TED, square mesh codend or both. The largest reduction was 96% for the longspine emperor (*L. genivittatus*, $\boldsymbol{\beta}_3$ parameter estimate of 0.04, Table 7.4.3) which was largely due to the square mesh codend. Catch rates of the red portunid crab (*P. rubromarginatus*) were reduced by 88% in nets with the TED and square mesh codend ($\boldsymbol{\beta}_3$ parameter estimate of 0.12, Table 7.4.3). Other species with large reductions due to the square mesh codend included the threadfin bream (*N. theodorei*), dusky leatherjacket (*P. otisensis*), the Caledonian stinger (*I. caledonicus*), the toadfish (*T. pallimaculatus*) and the paradise whiptail (*P. paradiseus*). The probability of capturing the eastern shovelnose ray *A. rostrata,* which was the largest of the bycatch species analysed and the most commonly encountered elasmobranch, was significantly reduced in nets with the TED installed compared to the net with the square mesh codend BRD only (Table 7.4.3). No significant reductions were detected for the other two elasmobranchs, *D. kuhli* and *D. leylandi*, probably because of their small size compared to *A. rostrata* which prevents them from being excluded by the TED.

Table 7.4.3. Effects of codend type on the catch rates of the commonly encountered bycatch species based on 236 measures (59 sites trawled x 4 nets). Generalised linear modelling was used to quantify the effects. Significant differences between codends ($P < 0.05$) are bolded and identified by different alphabetic characters (A, B, C or D). Parameter estimates for the normally distributed log transformed data [N(log)] were proportionally scaled so they could be compared to a standard net parameter value of 1. Values for the binomial data (B) are probabilities of capture. Standard errors in parentheses.

Species	Occurrence in 236 samples	Mean observed catch rate ($\mathrm{g\ ha^{-1}}$) in Standard net codend	Predicted probability of capture in Standard net codend	Predicted change in catch rates			Distribution type
				TED	Square mesh codend BRD	Square mesh codend BRD with TED	
Portunus rubromarginatus	**167**	**308.31 (50.66) A**	**-**	**1.09 (0.23) A**	**0.21 (0.04) B**	**0.12 (0.02) B**	**N(log)**
Portunus pelagicus	163	280.68 (51.36)	-	1.27 (0.24)	1.31 (0.25)	1.39 (0.27)	N(log)
Chaetodermis penicilligrus	106	81.15 (20.89)	-	1.39 (0.35)	1.08 (0.27)	1.02 (0.26)	N(log)
Inimicus caledonicus	**104**	**261.82 (71.00) A**	**-**	**0.91 (0.23) A**	**0.22 (0.05) B**	**0.40 (0.10) C**	**N(log)**
Nemipterus theodorei	**103**	**221.51 (48.73) A**	**-**	**1.24 (0.31) A**	**0.10 (0.02) B**	**0.15 (0.04) B**	**N(log)**
Paramonacanthus otisensis	**100**	**56.99 (11.46) A**	**-**	**0.77 (0.17) A**	**0.17 (0.04) B**	**0.14 (0.03) B**	**N(log)**
Lethrinus genevittatus	**98**	**531.42 (94.90) A**	**-**	**0.83 (0.27) A**	**0.04 (0.01) B**	**0.04 (0.01) B**	**N(log)**
***Pentaceraster* sp.**	**96**	**105.68 (20.18) A**	**-**	**0.57 (0.12) B**	**0.97 (0.20) A**	**0.94 (0.20) A**	**N(log)**
Halophila spinulosa	**74**	**71.09 (25.27) A**	**-**	**0.84 (0.21) A**	**0.44 (0.11) B**	**0.44 (0.11) B**	**N(log)**
Pseudorhombus spinosus	**74**	**27.25 (6.12) A**	**-**	**1.04 (0.16) A**	**0.67 (0.10) B**	**0.88 (0.13) AB**	**N(log)**
Callyspongia sp.	70	158.34 (45.45)	-	1.00 (0.18)	1.00 (0.18)	1.14 (0.20)	N(log)
Siganus fuscescens	**64**	**58.13 (16.34) A**	**-**	**1.19 (0.22) A**	**0.36 (0.07) B**	**0.44 (0.08) B**	**N(log)**
Paramonacanthus lowei	**62**	**-**	**0.46 (0.03) A**	**0.47 (0.03) A**	**0.07 (0.02) B**	**0.05 (0.02) B**	**B**
Aptychotrema rostrata	**62**	**-**	**0.27 (0.04) AB**	**0.21 (0.03) B**	**0.36 (0.03) A**	**0.19 (0.03) B**	**B**
Saurida grandisquamis	**61**	**201.39 (51.09) A**	**-**	**0.85 (0.18) A**	**0.19 (0.04) B**	**0.20 (0.04) B**	**N(log)**
Annachlamys flabellate	**54**	**27.32 (10.45) A**	**-**	**0.87 (0.12) A**	**0.50 (0.07) B**	**0.61 (0.08) B**	**N(log)**
***Stichopus* sp.**	**53**	**55.42 (27.10) AB**	**-**	**1.16 (0.23) A**	**0.98 (0.19) AB**	**0.77 (0.15) B**	**N(log)**
Pseudorhombus dupliciocellatus	**52**	**27.45 (8.30) A**	**-**	**0.99 (0.18) A**	**0.66 (0.12) B**	**0.65 (0.12) B**	**N(log)**
Grammatobothus polyophthalmus	**48**	**17.44 (6.87) AB**	**-**	**1.50 (0.27) A**	**0.89 (0.16) BC**	**0.64 (0.12) C**	**N(log)**
Torquigener pallimaculatus	**48**	**-**	**0.37 (0.03) A**	**0.38 (0.03) A**	**0.02 (0.03) B**	**0.03 (0.02) B**	**B**
Pseudomonacanthus peroni	47	-	0.25 (0.04)	0.24 (0.04)	0.15 (0.04)	0.15 (0.04)	B
Polycarpa sp.	46	94.17 (40.78)	-	1.07 (0.24)	0.79 (0.18)	0.84 (0.19)	N(log)
Sea urchin 3	46	70.99 (26.54)	-	0.85 (0.15)	1.05 (0.19)	0.88 (0.15)	N(log)
Holothuria ocellate	41	47.10 (16.93)	-	0.82 (0.15)	0.91 (0.16)	0.72 (0.13)	N(log)
Unidentified Bryozoan	41	55.84 (34.14)	-	0.75 (0.20)	1.19 (0.31)	0.88 (0.23)	N(log)

Species	**Occurrence in 236 samples**	**Mean observed catch rate (g ha^{-1}) in Standard net codend**	**Predicted probability of capture in Standard net codend**	**Predicted change in catch rates**			**Distribution type**
				TED	**Square mesh codend BRD**	**Square mesh codend BRD with TED**	
Choerodon cephalotes	**39**	**-**	**0.25 (0.03) A**	**0.25 (0.03) A**	**0.10 (0.02) B**	**0.05 (0.02) B**	**B**
Dysidea sp.	37	21.65 (8.73)	-	0.90 (0.16)	1.14 (0.20)	0.95 (0.16)	N(log)
Peronella sp.	36	24.18 (12.70)	-	0.91 (0.19)	0.94 (0.19)	1.30 (0.26)	N(log)
Charybdis natator	33	18.23 (10.50)	-	1.49 (0.49)	1.50 (0.49)	1.16 (0.38)	N(log)
Lobophora **sp.**	**33**	**34.73 (14.05) A**	**-**	**0.77 (0.16) AC**	**0.49 (0.10) B**	**0.55 (0.11) BC**	**N(log)**
Dasyatis kuhlii	33	-	0.15 (0.03)	0.15 (0.03)	0.13 (0.03)	0.12 (0.03)	B
Actinopyga miliaris	32	89.65 (33.31)	-	0.89 (0.11)	0.89 (0.11)	0.88 (0.11)	N(log)
Pentapodus paradiseus	**32**	**-**	**0.25 (0.03) A**	**0.22 (0.03) A**	**0.03 (0.02) B**	**0.03 (0.02) B**	**B**
Trachinocephalus myops	**31**	**19.43 (5.71) A**	**-**	**1.14 (0.13) A**	**0.62 (0.07) B**	**0.62 (0.07) B**	**N(log)**
Rhynchostracion nasus	29	-	0.15 (0.03)	0.11 (0.03)	0.15 (0.03)	0.09 (0.03)	B
Dasyatis leylandi	28	-	0.15 (0.04)	0.11 (0.03)	0.09 (0.04)	0.13 (0.04)	B
Abalistes stellaris	25	14.05 (5.85)	-	0.94 (0.16)	0.80 (0.13)	0.80 (0.13)	N(log)
Bohadschia marmorata	**23**	**-**	**0.14 (0.03) A**	**0.07 (0.03) AB**	**0.05 (0.02) B**	**0.14 (0.03) A**	**B**
Sargassum racamosa	23	-	0.12 (0.03)	0.13 (0.03)	0.07 (0.02)	0.07 (0.02)	B
Anchisomus multistriatus	**21**	**-**	**0.17 (0.03) A**	**0.03 (0.02) B**	**0.10 (0.03) AB**	**0.05 (0.02) B**	**B**
Gymnocranius audleyi	**19**	**20.65 (9.40) AB**	**-**	**1.10 (0.13) A**	**0.83 (0.10) B**	**0.80 (0.10) B**	**N(log)**
Upeneus luzonius	**19**	**37.12 (16.92) A**	**-**	**0.85 (0.10) A**	**0.65 (0.08) B**	**0.62 (0.07) B**	**N(log)**
Tragulichthys jaculiferus	13	-	0.08 (0.03)	0.07 (0.02)	0.05 (0.02)	0.02 (0.01)	B
Diagramma pictum	**12**	**-**	**0.07 (0.02) AB**	**0.08 (0.02) A**	**0.03 (0.02) AB**	**0.02 (0.01) B**	**B**
Charybdis feriatus	11	-	0.05 (0.02)	0.05 (0.02)	0.02 (0.02)	0.07 (0.02)	B
Nephthea sp. 2	11	-	0.07 (0.01)	0.05 (0.01)	0.03 (0.01)	0.03 (0.01)	B
Holothuria fuscogliva	7	-	0.03 (0.02)	0.07 (0.02)	0.02 (0.02)	2×10^{-6} (0.0001)	B
Holothurian sp.	6	-	0.03 (0.01)	0.02 (0.00004)	0.03 (0.01)	0.02 (0.00004)	B
Scolopsis monogramma	6	19.75 (14.01)	-	0.94 (0.08)	0.87 (0.07)	0.94 (0.08)	N(log)

Obtaining meaningful length measurements for some species groups (i.e., seagrass *H. spinulosa*, algae *S. racamosa* and *Lobophora* sp., Bryozoans) was problematic and as a result the effects on length were limited to 41 taxa (Table 7.4.4). Significant differences between codend types were detected for 15 species. For the majority of those species where a significant effect was detected, the mean length was found to increase in nets with a square mesh codend, suggesting that some smaller individuals escaped through the square meshes. The largest increase was for the starry triggerfish (*A. stellaris*) which increased from a mean of 92.7 mm SL in the standard net to 187.5 mm SL in the net with both the TED and square mesh codend (Table 7.4.4).

The effect of the TED by itself was less marked and affected the size of five species. Significant increases were detected for the red portunid crab (*P. rubromarginatus*), the tassle filefish (*C. penicilligrus*) and the fan scallop (*A. flabellate*), while significant decreases were detected for the threadfin bream (*N. theodorei*) and longspine emperor (*L. genevittatus*).

Table 7.4.4. Predicted mean length (in mm) of bycatch species from the four codend types based on 236 measures (59 sites trawled x 4 nets). Generalised linear modelling was used to estimate the means using a normal distribution with identity link function. Significant differences between codends ($P < 0.05$) are bolded and identified by different alphabetic characters (A, B, C or D). Standard errors in parentheses.

Species	**Occurrence in 236 samples**	**Predicted mean length**			
		Standard net codend	**TED only**	**Square mesh codend BRD only**	**Square mesh codend and TED together**
Portunus rubromarginatus	**167**	**52.01 (0.28) A**	**53.03 (0.28) B**	**54.10 (0.51) B**	**53.44 (0.64) B**
Portunus pelagicus	163	132.89 (1.39)	133.95 (1.29)	136.08 (1.21)	136.10 (1.32)
Chaetodermis penicilligrus	**106**	**117.18 (4.50) A**	**136.08 (4.03) B**	**144.53 (5.18) B**	**157.46 (4.78) C**
Inimicus caledonicus	**104**	**127.76 (2.13) A**	**127.63 (2.14) A**	**144.84 (5.44) B**	**143.90 (3.96) B**
Nemipterus theodorei	**103**	**157.47 (1.31) A**	**152.07 (1.00) B**	**156.03 (5.08) AB**	**162.59 (2.74) A**
Paramonacanthus otisensis	100	89.61 (0.94)	87.22 (1.09)	86.39 (3.18)	88.10 (3.86)
Lethrinus genevittatus	**98**	**136.10 (1.50) A**	**129.57 (1.61) B**	**124.80 (5.54) B**	**156.35 (5.81) C**
Pentaceraster sp.	96	144.37 (4.48)	143.55 (4.84)	154.92 (3.49)	154.02 (3.40)
Pseudorhombus spinosus	74	198.72 (4.59)	192.24 (4.11)	197.85 (6.86)	206.79 (5.90)
Siganus fuscescens	**64**	**122.12 (2.14) A**	**117.69 (2.04) A**	**113.93 (8.05) A**	**140.39 (6.42) B**
Paramonacanthus lowei	**62**	**103.01 (1.88) AB**	**100.82 (1.51) A**	**127.11 (9.54) B**	**103.95 (7.61) AB**
Aptychotrema rostrata	63	554.50 (23.80)	539.20 (35.10)	583.10 (20.90)	576.30 (31.50)
Saurida grandisquamis	61	306.37 (7.78)	294.33 (6.95)	*	284.91 (56.61)
Annachlamys flabellata	**54**	**54.42 (0.57) A**	**57.08 (0.64) B**	**55.96 (0.92) AB**	**56.85 (0.84) B**
Stichopus sp.	53	250.20 (30.20)	217.80 (26.70)	238.60 (34.10)	247.90 (41.80)
Pseudorhombus dupliciocellatus	52	191.35 (7.08)	190.81 (6.19)	209.14 (13.15)	193.50 (15.64)
Grammatobothus polyophthalmus	48	171.79 (4.96)	160.14 (3.22)	167.65 (6.94)	177.34 (11.72)
Torquigener pallimaculatus	**48**	**93.61 (2.85) A**	**90.42 (2.05) A**	**52.47 (17.55) B**	**93.61 (2.85) A**
Pseudomonacanthus peroni	47	196.37 (7.39)	206.10 (8.45)	212.87 (12.48)	208.34 (10.59)
Sea urchin 3	**46**	**68.44 (2.62) A**	**60.99 (2.94) A**	**77.30 (3.77) B**	**66.77 (3.57) AB**
Holothuria ocellata	**41**	**175.41 (6.17) AB**	**162.67 (10.12) A**	**192.04 (8.40) B**	**155.96 (11.31) A**
Choerodon cephalotes	39	156.58 (7.04)	166.78 (7.78)	171.65 (15.50)	193.87 (25.31)
Peronella sp.	36	122.39 (5.61)	114.40 (6.85)	131.23 (7.63)	120.56 (3.45)
Charybdis natator	33	91.22 (12.45)	86.80 (8.59)	86.43 (7.08)	113.25 (13.86)
Dasyatis kuhlii	33	278.10 (17.30)	286.10 (14.70)	273.00 (15.50)	270.00 (20.10)
Actinopyga miliaris	**32**	**185.69 (8.38) A**	**195.88 (7.88) A**	**155.60 (8.41) B**	**192.13 (7.17) A**

Species	**Occurrence in 236 samples**	**Predicted mean length** **Standard net codend**	**TED only**	**Square mesh codend BRD only**	**Square mesh codend and TED together**
Pentapodus paradiseus	32	156.57 (3.79)	157.75 (5.40)	144.57 (12.95)	124.74 (17.59)
Trachinocephalus myops	31	172.44 (7.84)	189.24 (5.25)	*	*
Rhynchostracion nasus	**29**	**130.70 (13.00) A**	**128.50 (14.40) A**	**211.20 (12.20) B**	**155.70 (32.70) AB**
Dasyatis leylandi	28	192.50 (26.30)	*	172.70 (53.50)	169.40 (62.40)
Abalistes stellaris	**25**	**92.70 (21.00) AC**	**117.10 (12.90) AB**	**141.60 (25.30) BD**	**187.50 (30.20) CD**
Bohadschia marmorata	23	180.10 (15.40)	157.30 (37.80)	180.10 (35.20)	197.60 (14.20)
Anchisomus multistriatus	21	312.29 (6.32)	332.29 (20.16)	342.29 (9.07)	312.29 (6.32)
Gymnocranius audleyi	**19**	**118.92 (3.65) A**	**118.92 (3.65) AB**	**101.02 (34.77) A**	**180.84 (13.35) B**
Upeneus luzonius	19	145.44 (3.54)	142.98 (4.42)	139.78 (12.65)	130.00 (18.30)
Tragulichthys jaculiferus	13	127.50 (53.70)	170.00 (58.60)	155.00 (62.10)	127.50 (53.70)
Diagramma pictum	12	180.30 (24.60)	182.40 (21.30)	180.30 (24.60)	241.50 (62.20)
Charybdis feriatus	11	132.50 (5.27)	164.50 (8.82)	132.50 (5.27)	124.50 (6.67)
Holothuria fuscogliva	7	*	*	*	*
Holothurian sp.	6	*	*	*	*
Scolopsis monogramma	6	220.24 (8.32)	220.24 (8.32)	*	189.52 (12.84)

* Too few individuals sampled to predict mean length

Table 7.4.5. Species that contributed 90% of the dissimilarity between the shallow (20 m) and deepwater (50 m) groups in the Queensland scallop fishery bycatch.

Species/Taxa	20 m depth group mean catch rate (g ha^{-1})	50 m depth group mean catch rate (g ha^{-1})	Average dissimilarity	Dissimilarity/Standard deviation	Contribution to dissimilarity %	Cumulative % dissimilarity
Unidentified Sponge	7218.73	1286.51	4.73	1.09	5.92	5.92
Portunus pelagicus	586.51	62.91	4.52	1.1	5.67	11.59
Lethrinus genivittatus	553.73	27.88	3.23	1.02	4.04	15.63
Nemipterus theodorei	88.78	145.57	2.81	1.09	3.52	19.15
Rubble	153.36	57.93	2.64	0.74	3.3	22.45
Chaetodermis penicilligrus	80.95	13.58	2.63	0.83	3.29	25.74
Portunus rubromarginatus	191.28	71.93	2.56	1.21	3.21	28.95
Pentaceraster sp.	145.4	32.27	2.46	0.85	3.08	32.03
Inimicus caledonicus	254.07	3.49	2.42	1.16	3.03	35.06
Pseudorhombus	2.35	48	2.32	1.1	2.9	37.96
Aptychotrema rostrata	133.42	43.35	2.07	0.71	2.59	40.56
Halophila spinulosa	69.68	56.53	1.74	0.7	2.18	42.74
Unidentified Crinoid	1.96	20.12	1.74	0.68	2.18	44.92
Pseudorhombus spinosus	22.93	12.26	1.67	0.71	2.09	47.01
Saurida grandisquamis	86.32	24.12	1.64	0.78	2.05	49.07
Trachinocephalus myops	10.62	44.14	1.53	0.86	1.92	50.98
Siganus fuscescens	58.49	0.74	1.41	0.68	1.77	52.75
Pseudomonacanthus peroni	45.69	27.68	1.41	0.57	1.76	54.51
Grammatobothus	2.34	26.35	1.37	0.79	1.72	56.23
Paramonacanthus otisensis	28.59	11.3	1.34	0.86	1.68	57.9
Polycarpa sp.	58.08	13.56	1.31	0.7	1.64	59.54
Nephthya sp. *4*	0	35.48	1.27	0.51	1.59	61.14
Pristotis jerdoni	19.17	18.03	1.26	0.93	1.57	62.71
Peronella sp.	11.76	7.96	1.24	0.59	1.56	64.26
Dasyatis leylandi	13.29	13.26	1.18	0.56	1.48	65.74
Sea urchin 3	173.89	0	1.13	0.51	1.41	67.15
Holothuria ocellata	9.68	17.33	1.04	0.56	1.31	68.46
Ostracion nasus	1.14	38.69	1.02	0.51	1.28	69.74
Dasyatis kuhlii	29.29	17.41	1	0.52	1.25	70.99
Paramonacanthus lowei	1.99	11.47	0.97	0.73	1.22	72.21
Apistus carinatus	5.24	9.33	0.93	0.72	1.16	73.37

Species/Taxa	**20 m depth group mean catch rate (g ha^{-1})**	**50 m depth group mean catch rate (g ha^{-1})**	**Average dissimilarity**	**Dissimilarity/Standard deviation**	**Contribution to dissimilarity %**	**Cumulative % dissimilarity**
Sargassum racamosa	46.92	0.91	0.91	0.44	1.14	74.5
Stellaster equestris	0.46	7.54	0.88	0.62	1.11	75.61
Bohadschia marmorata	9.08	21.83	0.86	0.39	1.08	76.69
Engyprosopon grandisquama	4.6	5.03	0.86	0.7	1.07	77.76
Choerodon cephalotes	73.31	0	0.84	0.55	1.05	78.82
Upeneus asymmetricus	12.02	4.01	0.84	0.63	1.05	79.87
Basket star	14.14	7.56	0.83	0.53	1.04	80.9
Gymnocranius audleyi	0.18	52.51	0.82	0.5	1.03	81.93
Annachlamys flabellata	12.52	1.85	0.77	0.64	0.97	82.9
Charybdis natator	29.56	0.05	0.75	0.47	0.94	83.84
Pentapodus paradiseus	42.16	6.89	0.68	0.56	0.85	84.69
Torquigener pallimaculatus	5.66	4.66	0.62	0.58	0.78	85.47
Stichopus sp.	73.42	0	0.59	0.33	0.73	86.2
Portunus sanguinolentus	0.39	9.04	0.58	0.43	0.73	86.93
Tragulichthys jaculiferus	9.21	7.4	0.56	0.35	0.71	87.63
Lepidotrigla argus	0	8.57	0.53	0.49	0.66	88.29
Sepia papuensis	13.53	1.12	0.5	0.5	0.62	88.91
Amphimedon sp.	1.38	11.49	0.47	0.33	0.59	89.5
Anchisomus multistriatus	86.82	0	0.47	0.26	0.58	90.09

7.4.4 Variation in bycatch community structure

Multidimensional scaling (MDS) was carried out using all 236 sub-samples and the catch rates of 82 species that were present in 5% or more of the sub-samples. The resulting stress value was 0.17 for a three-dimensional ordination. Analysis of similarities (ANOSIM procedure in PRIMER) revealed that bycatch assemblages differed significantly between depths (global $R = 0.240$, $P < 0.001$), with the largest R-statistic value (i.e., greatest difference) of 0.447 between the shallowest (20 m) and deepest (50 m) categories. Catch rates for unidentified sponges, blue swimmer crabs (*P. pelagicus*) and longspine emperor (*L. genevittatus*) were significantly higher for the 20 m group compared to the 50 m group and together accounted for over 15% of the dissimilarity (Table 7.4.5).

Bycatch assemblages were also affected by latitude (global $R = 0.248$, $P < 0.001$, Figure 7.4.3). The largest difference was between the 24.0 °S group and the 22.5 °S group (R-statistic = 0.668) and attributed largely to unidentified sponges, which were much more abundant at lower latitudinal sites, and portunid crabs (*P. pelagicus* and *P. rubromarginatus*) which were more abundant at higher latitudes. Other significant differences were detected between the 24.0 °S group and the 22.5 °S group (R-statistic = 0.566), the 24.0 °S group and the 23.5 °S group (R-statistic = 0.525), and the 25.0 °S group and the 22.5 °S group (R-statistic = 0.505).

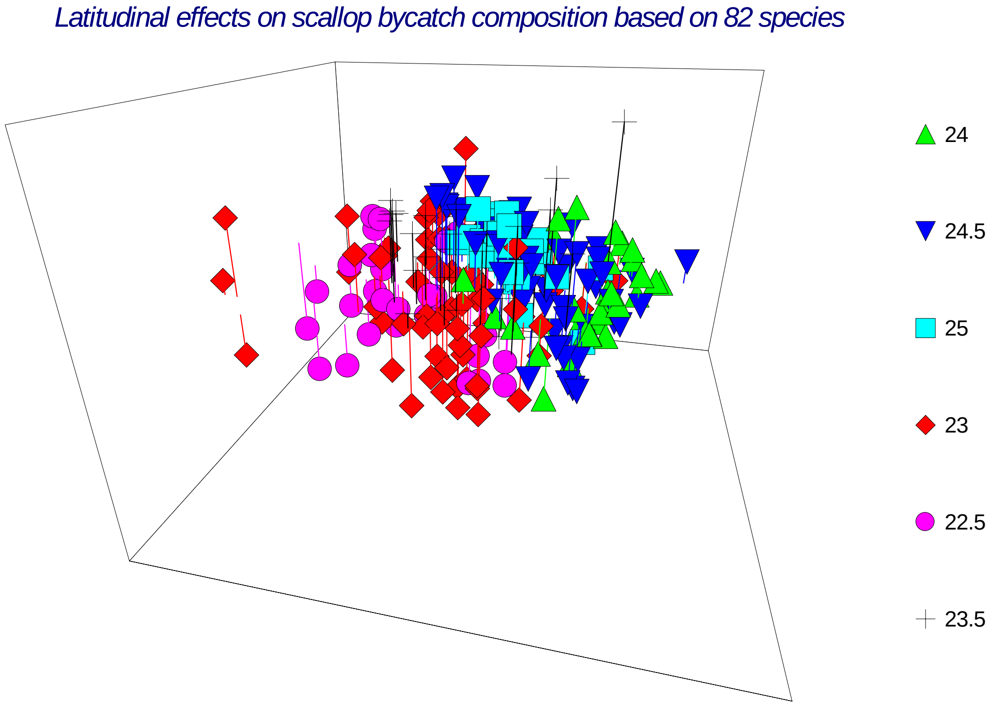


Figure 7.4.3. Multidimensional scaling of 82 species of bycatch from 236 trawl locations in the Queensland scallop fishery showing group formations based on latitude. Legend refers to latitudes rounded to the nearest 0.5 °S.

ANOSIM also revealed that bycatch assemblages differed significantly between codend types (global $R = 0.181$, $P < 0.001$) with the largest difference between the TED and the square mesh coded (R-statistic = 0.334, Table 7.4.6). Species that contributed most to the dissimilarity between these groups were a) unidentified sponges, which were about four times more abundant in the square mesh codend, and b) the threadfin bream (*N. theodorei*) and longspine emperor (*L. genevittatus*), which were about 20 times more abundant in the TED net. Collectively these three species accounted for 13.7% of the dissimilarity. Some species that contributed to the dissimilarity were completely absent from the square mesh codends, including the longfin waspfish (*Apistus carinatus*), the painted lizardfish (*Trachinocephalus myops*) and the mud flathead (*Ambiserrula jugosa*). None of the species that contributed to the dissimilarity were absent from the TED nets. The results suggest that the square mesh codends effectively remove much of the bycatch, including entire species, and is therefore responsible for most of the dissimilarity between the TED and square mesh codend groups.

The clustering of groups can be seen in Figure 7.5.1, where bycatch samples that were taken from nets with square mesh codends tend to cluster on the right-hand side of the graph and those taken from nets without the square mesh codends (i.e., TED and standard net) are largely distributed on the left-hand side.

Table 7.4.6 *R*-statistic values and significance levels for differences in bycatch community structure between codend types.

Groups	***R*-statistic**	**Significance level**
TED, standard net	0.033	0.018
TED, TED and square mesh coded	0.235	0.001
TED, square mesh coded	0.334	0.001
standard net, TED and square mesh coded	0.212	0.001
standard net, square mesh coded	0.225	0.001
TED and square mesh coded, square mesh coded	0.047	0.002

7.5 DISCUSSION

The study demonstrated a practical gear-based method for reducing total bycatch in the Queensland scallop fishery by 77% ($\boldsymbol{\beta}_3$ parameter estimate of 0.23, Table 7.4.1), based on deploying a TED and square mesh codend BRD together in the net, compared to a standard scallop fishing net with no bycatch reduction devices installed. Importantly, the reduction was achieved with no reduction in the catch rate of legal sized (≥ 95 mm shell height) scallops and a reduction in the number of undersized scallops in the catch of 63%.

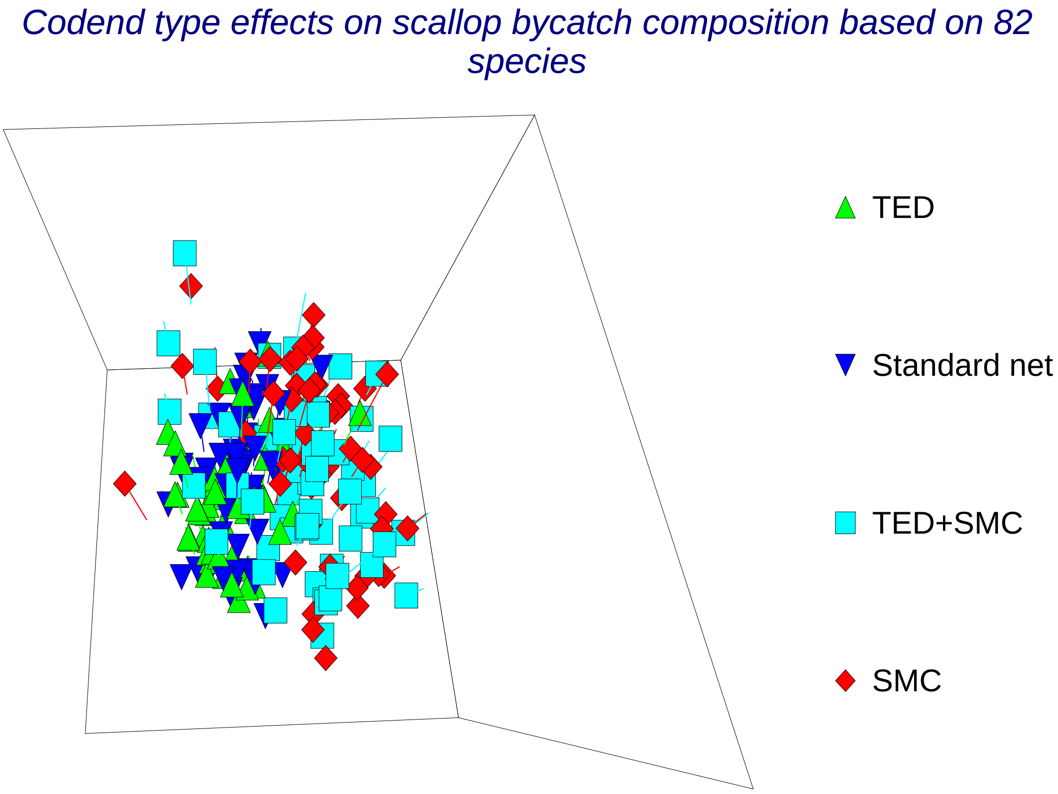


Figure 7.5.1. Multidimensional scaling of 82 bycatch species from 236 trawl locations in the Queensland scallop fishery showing group formations based on codend type. Note that bycatch samples without square mesh codends (SMC) (i.e., blue and green triangles) largely distributed to the left-hand side of the MDS while those with square mesh codends (blue squares and red diamonds) are largely distributed on the right-hand side.

The large reduction in bycatch was achieved because the two devices (i.e., the TED and the square mesh codend) excluded different components of the bycatch and when used together they complemented each other resulting in the exclusion of the great majority of the bycatch. The TED by itself was particularly effective at excluding large bycatch fauna which comprised 64% of the total bycatch weight and was dominated by large sponges (92% of the large bycatch was sponge). The TED was also effective at reducing other large fauna such as sharks and rays, but because these were infrequent and contributed only a minor component of the bycatch weight (8% of the large bycatch fauna) no specific analyses were undertaken. The square mesh codend by itself was highly effective at excluding the smaller species (i.e., bycatch excluding large fauna, β_3 parameter estimate of 0.44, Table 7.4.1). When used together the reductions from both devices were largely additive, effectively excluding 77% of the total bycatch (β_3 parameter estimate of 0.23, Table 7.4.1).

7.5.1 Extrapolating the charter results to the scallop fishery

If the results are considered with logbook data on catch and effort then collectively they suggest that the total weight of bycatch in the scallop fishery could be reduced by several thousand tonnes per year. For example, scallop landings for the period 1988 to

1999 averaged 1100 tonnes of meat per year (Williams, 2002), which equates to approximately 5500 tonnes of unshucked scallops per year. Measurements of bycatch obtained directly from scallop fishers over the last two years indicate that for every 1 kg of unshucked legal sized scallops caught in a standard net there was about 2.5 kg of bycatch – a ratio of 2.5:1. Note that measures of the ratio obtained from the charter were higher than this; a mean of 4.59 kg legal sized scallop to a mean of 15.89 kg total bycatch (Table 7.4.1) which equates to a ratio of 3.5:1. By using the 2.5:1 ratio, estimates of the scallop meat weight logbook data from 1988–1999 and simple extrapolation, it can be estimated that about 13,750 tonnes of bycatch was produced by the scallop fishery annually over the period. If all of the scallop trawlers used the TED and square mesh codend that was trialled herein, and the 77% reduction was extrapolated to the scallop fleet, it would equate to a reduction in bycatch of about 10, 588 tonnes to 3163 tonnes annually, with no loss of the legal sized scallop catch. This reduction estimate is likely to be conservative as larger reductions would be obtained by using the ratio value of 3.5:1 obtained from the charter.

7.5.2 Effects on scallops

There was no significant difference between codend types on the catch rate of legal sized scallops, but nets with the square mesh codend were found to significantly reduce undersize scallop catch rates (Table 7.4.1). The $\boldsymbol{\beta}_3$ parameter estimate of 0.68 (Table 7.4.1) that was obtained for the TED and square mesh codend together, equates to a 32% reduction in weight. Because the undersized scallops are small, the observed reduction by number was much greater, at 63%. Suuronen and Millar (1992) found that 36 mm square mesh codends retained significantly fewer small herring compared to diamond mesh codends of the same mesh size in the northern Baltic Sea herring (*Clupea harengus*) fishery. While the incidental fishing mortality on undersized scallops from the fishery is unknown, it may be considerable and therefore be lowering the maximum sustainable yield from the fishery. Any reduction in the incidental mortality on the stock should therefore be seen as highly desirable. It is noteworthy that while nets with the square mesh codends significantly reduced the number of undersized scallops that were retained, brought to the surface, dropped on the sorting tray and thrown back over the side of the vessel, it is unknown whether those undersized scallops that passed through the square meshes and escaped experienced any additional mortality as a result. It seems likely that those that escaped through the square meshes would have experienced less incidental mortality than those that were retained.

7.5.3 Effects on Moreton Bay bugs

Both the TED and the square mesh codend significantly reduced the catch rate of legal sized (≥ 75 mm CW) lobsters (*T. orientalis*) and together lowered catch rates by 28% ($\boldsymbol{\beta}_3$ parameter estimate of 0.72, Table 7.4.2). Some of the loss was likely to be due to the TED excluding large amounts of sponges. Before they are expelled, the sponges accumulate in front of the TED. It seems likely that the sponges prevent the lobsters from passing though the TED and that they escape with the sponges as they are expelled through the TED escape opening. Some fishers have suggested that the lobsters walk forward inside a trawl net and escape through the TED escape hole. On several occasions throughout the charter, lobsters were observed trying to escape through the square mesh codends tail first and as a result, some loss from the square mesh was expected.

To reduce the loss of legal sized lobsters from TEDs, it is essential that sponges be excluded as quickly as possible. This would reduce the problems associated with clogging. One technical aspect to consider when constructing a TED is the angle of the grid. Most scallop fishers have their own thoughts concerning the angle of the grid but an angle of about 60^{o} appears to be a good starting point. Bent deflector bars also appear to be an important feature of an efficient TED.

Both devices also significantly lowered the catch rate of undersized lobsters, but the square mesh codend was particularly effective and by itself reduced catch rates by 74% ($\boldsymbol{\beta}_3$ parameter estimate of 0.26, Table 7.4.2). When used together, the TED and square mesh codend reduced undersize lobster catch rates by 76% ($\boldsymbol{\beta}_3$ parameter estimate of 0.24, Table 7.4.2). As was the case with the undersize scallop catch rates, any reduction in the incidental capture or mortality of undersized lobsters is likely to have a benefit to the lobster population size and harvest, and for these reasons should be viewed positively.

7.5.4 Effects on individual bycatch species

Of the 46 species that could be analysed using GLM, 25 (54%) were found to have statistically significant reductions that were attributed to the TED, the square mesh codend or both (Table 7.4.3). The largest reductions were attributed to the square mesh codend, or the square mesh codend and TED together. For example, the square mesh codend by itself reduced the catch rates of threadfin bream (*N. theodorei*) and longspine emperor (*L. genevittatus*) by 90% or more. The reason the device was so effective is because a) it surrounds the small fish and invertebrates with multiple points of escapement and b) individuals do not have to expend energy to find an escape hole and pass through it, but rather many species may simple fall through the large open square meshes.

7.5.5 Variation in bycatch community structure

Large unidentified sponges dominated the bycatch and made up about 60% of the total bycatch weight. The large bycatch fauna also included relatively infrequent catches of elasmobranchs. The remaining dominant fauna included portunid crabs, demersal and benthic fish, small unidentified sponges, sea urchins, holothurians, molluscs, algae and seagrass. Laurenson et al. (1993) examined the bycatch from a similar otter trawl fishery for *A. japonicum ballotti* in Western Australia and found it was comprised of 150 species of teleosts, elasmobranchs and invertebrates.

Bycatch composition varied significantly with depth (Table 7.4.5), latitude (Figure 7.4.3) and codend type (Figure 7.5.1). The global *R* values for the latitude (0.248) and depth effects (0.240) were higher than codend effects (0.181), suggesting that latitude and depth had a greater effect on bycatch composition than codend type. Watson et al. (1990) examined variation in the benthic faunal communities associated with the red spot king prawn fishery in Central Queensland. They found that faunal composition was affected more by location of sample sites than by the time (i.e., month). They also differentiated the communities into nearshore, midshelf and inter-reef groups and found weakly separated wet and dry season temporal groupings. Veale et al. (2000) examined variation in bycatch assemblages from the scallop dredge fishing grounds in the North Irish Sea in relation to depth, sediment type and fishing effort. They concluded that bycatch diversity decreased with increased fishing disturbance and suggested that it was due to the removal of sensitive species and habitat homogenisation. In the current study the relationship between fishing effort and bycatch structure was not examined. Fishing effort may be an important factor affecting the bycatch but demonstrating that it has caused changes, rather than simply showing a correlation would be challenging.

TEDs and BRDs have been introduced progressively throughout the Queensland trawl fishery over the last few years. Both devices became mandatory in the scallop sector in July 2001. While TEDs were introduced specifically to reduce the incidental capture of turtles, they can also significantly lower the catch rate of bycatch, as has been shown here. The square mesh codend is one of the five recognised BRDs listed for use in the fishery's management plan. Clearly, if the fishery managers and conservation agencies are interested in assessing the reduction in bycatch in the fishery then they need to consider the effectiveness of both TEDs and BRDs.

While it is beyond the capacity of this current research project to assess the effectiveness of each different combination of TED and BRD in each sector of the fishery, the results from this particular charter are very promising. They clearly indicate that bycatch in the scallop fishery can be significantly reduced by using a square mesh codend BRD with a TED, with no significant loss of commercial size scallop catch. While the results are promising, they should be interpreted with caution. For example, all of the results reported here are based on an eight-day trial. As such, they do not consider any possible long-term problems that may or may not be associated with the square mesh codends, such as knot slippage or higher rates of wear and tear.

7.6 REFERENCES

Alverson, D.L., Freeberg, M.H., Pope, J.G., Murawski, S.A., 1994. A global assessment of fisheries bycatch and discards. FAO Fish. Tech. Pap. 330, 233 pp.

Barker, J., O'Sullivan, S., Jebreen, E., Roy, D., Kennedy, C., 2004. Fisheries long-term monitoring program. Benthic marine fauna composition in the Queensland scallop fishery area in 2000 and 2002. Department of Primary Industries and Fisheries, Queensland. Information Series QI04096, p. 74.

Bremec, C.S., Lasta, M.L., 2002. Epibenthic assemblage associated with scallop (*Zygochlamys patagonica*) beds in the Argentinian shelf. Bull. Mar. Sci. 70, 89-105.

Brewer, D., Rawlinson, N., Eayrs, S., Burridge, C.Y., 1998. An assessment of bycatch reduction devices in a tropical Australian prawn trawl fishery. Fish. Res. 36, 195-215.

Broadhurst, M.K., 2000. Modifications to reduce bycatch in prawn trawls: A review and framework for development. Rev. Fish Biol. Fish. 10, 27-60.

Broadhurst, M.K., Larsen, R.B., Kennelly, S.J., McShane, P.E., 1999. Use and success of composite square-mesh codends in reducing bycatch and in improving size-selectivity of prawns in Gulf St. Vincent, South Australia. Fish. Bull. 97, 434-448.

Broadhurst, M.K., Millar, R.B., Kennelly, S.J., Macbeth, W.G., Young, D.J., Gray, C.A., 2004. Selectivity of conventional diamond- and novel square-mesh codends in an Australian estuarine penaeid-trawl fishery. Fish. Res. 67, 183-194.

Clarke, K.R., Warrick, R.M., 1994. Change in marine communities: an approach to statistical analysis and interpretation. Plymouth Marine Laboratories, Plymouth, p. 144.

Currie, D.R., Parry, G.D., 1994. The impact of scallop dredging on a soft sediment community using multivariate techniques. Mem. Queensl. Mus. 36, 315-326.

Dichmont, C.M., Dredge, M.C.L., Yeomans, K., 2000. The first large-scale fishery-independent survey of the saucer scallop *Amusium japonicum balloti* in Queensland, Australia. J. Shellfish Res. 19, 731-739.

DuPaul, W.D., Brust, J.C., Kirkley, J.E., 1996. Bycatch in the United States and Canadian Sea Scallop Fisheries. Alaska Sea Grant College Program, Fairbanks, Alaska (USA).

Eayrs, S., Buxton, C., McDonald, B., 1997. A guide to bycatch reduction in Australian prawn trawl fisheries. Australian Maritime College.

GenStat, 2005. GenStat, 8th ed. Lawes Agricultural Trust.

Hall, M., Alverson, D.L., Metuzals, K., 2000. By-Catch: Problems and Solutions. Mar. Pollut. Bull. 41, 204-219.

Hall, S.J., Mainprize, B.M., 2005. Managing by-catch and discards: how much progress are we making and how can we do better? Fish Fish. 6, 134-155.

Harris, A.N., Poiner, I.R., 1990. By-catch of the Prawn Fishery of Torres Strait; Composition and Partitioning of the Discards into Components that Float or Sink. Aust. J. Mar. Freshw. Res. 41, 37-52.

Kerrigan, B., Gaddes, S., Norris, W., 2004. Review of the sustainability of fishing effort in the Queensland East Coast Trawl Fishery. The State of Queensland, Department of Primary Industries and Fisheries, Report QI04067., p. 267.

Laurenson, L.J.B., Unsworth, P., Penn, J.W., Lenanton, R.C.J., 1993. The impact of trawling for saucer scallops and western king prawns on the benthic communities in coastal waters off south Western Australia. Fisheries Department of Western Australia, p. 93.

Montgomery, D.C., 1997. Design and Analysis of Experiments, 4th ed. John Wiley and Sons.

O'Neill, M.F., Courtney, A.J., Good, N.M., Turnbull, C.T., Yeomans, K.M., Staunton Smith, J., Shootingstar, C., 2005. Reference point management and the role of catch-per-unit effort in prawn and scallop fisheries. FRDC Project #1999/120 Final Report. Department of Primary Industries and Fisheries, Queensland QO 05001, p. 265.

Robins, J., Courtney, A., 1998. Status report on bycatch within the Queensland trawl fishery. In: Buxton, C., Eayrs, S., (Ed.), Establishing meaningful targets for bycatch reduction in Australian fisheries. Australian Society for Fish Biology, Sydney, Hobart 24-25 September 1998, pp. 24-45.

Sterling, D.J., 2005. Modelling the Physics of Prawn Trawling For Fisheries Management. School of Applied Physics. Curtin University of Technology, Western Australia, Perth, p. 236.

Suuronen, P., Millar, R.B., 1992. Size Selectivity of Diamond and Square Mesh Codends in Pelagic Herring Trawls – Only Small Herring Will Notice the Difference. Can. J. Fish. Aquat. Sci. 49, 2104-2117.

Thorsteinsson, G., 1992. The use of square mesh codends in the Icelandic shrimp (*Pandalus borealis*) fishery. Fish. Res. 13, 255-266.

Veale, L.O., Hill, A.S., Hawkins, S.J., Brand, A.R., 2000. Effects of long-term physical disturbance by commercial scallop fishing on subtidal epifaunal assemblages and habitats. Mar. Biol. 137, 325-337.

Veale, L.O., Hill, A.S., Hawkins, S.J., Brand, A.R., 2001. Distribution and damage to the by-catch assemblages of the northern Irish Sea scallop dredge fisheries. J. Mar. Biol. Assoc. U.K. 81, 85-96.

Watson, R.A., Dredge, M.L.C., Mayer, D.G., 1990. Spatial and seasonal variation in demersal trawl fauna associated with a prawn fishery on the central Great Barrier Reef, Australia. Aust. J. Mar. Freshw. Res. 41, 65-77.

Williams, L.E., 2002. Queensland's Fisheries Resources: current condition and recent trends 1988-2000. Department of Primary Industries, Brisbane, p. 180.

8 Winter (diver) whiting trawl bycatch in southern Hervey Bay

I. W. Brown, A. J. Courtney, M. J. Campbell, K. E. Chilcott and M. McLennan

8.1 ABSTRACT

A four-night research charter on board the commercial fishing vessel *Lewis Venture* was undertaken in June 2002 in the the southern end of Hervey Bay to examine the variation in prawn and bycatch catch rates, particularly recreationally important diver whiting (*Sillago maculata*). The effects of a) areas that were open and periodically closed to trawling, and b) different combinations of bycatch reduction devices (BRDs) were assessed. Levels of fishing effort in the closed area were also examined using Vessel Monitoring System (VMS) data. A Wick's fish-eye BRD, which is commonly used by vessels in the area, was tested with and without a turtle excluder device (TED). A total of 96 measurements of tiger prawn, bycatch and whiting catches were obtained. Catch rates of whiting were significantly higher in the closed area, but unaffected by codend treatment type (i.e., the TED or BRD). The catch rates of non-whiting bycatch, comprising 186 species (see Appendix 4), did not differ between open and closed areas, or between codend treatment type. Catch rates of tiger prawns were significantly higher inside the closed area, but were not affected by the codend treatment type. Levels of fishing effort in the closed area have declined in recent years, possibly because trawler operators can no longer retain and market whiting. Our results suggest that the types of TEDs and BRDs that fishers are using in the area are unlikely to have any effect on the whiting catch rates, or on most of the other bycatch species, with the possible exception of large species such as turtles, sharks and rays.

8.2 INTRODUCTION

The *Fisheries (East Coast Trawl) Management Plan 1999* (Reprint No. 2a) contains a Review Event relating to trawl bycatch of winter or diver whiting (*Sillago maculata*) in the southern Hervey Bay trawl closure area. The trigger for this review event is the result of a scientific study, and is formally stated in the Plan as follows: (*A review will be triggered if) The chief executive accepts a scientific study or survey that shows the level of winter whiting bycatch between 1 April and 1 June has not significantly declined in the area mentioned in schedule 3, section 72(1),49 before 2003.*

The area referred to in Schedule 3 Sect 72 is the Southern Hervey Bay (SHB) closure area (Figure 8.2.1). The closure period is the four months from July to October inclusive, but the "test" period (for the purposes of this review trigger) is April/May. While it is unclear whether the bycatch change was to be measured between years or from the beginning to the end of the test period, it is has been assumed for the purposes of this exercise that the former was intended. It is also assumed that in referring to "bycatch" the legislation means "total quantity" rather than "catch rate or catch per unit effort (CPUE)".

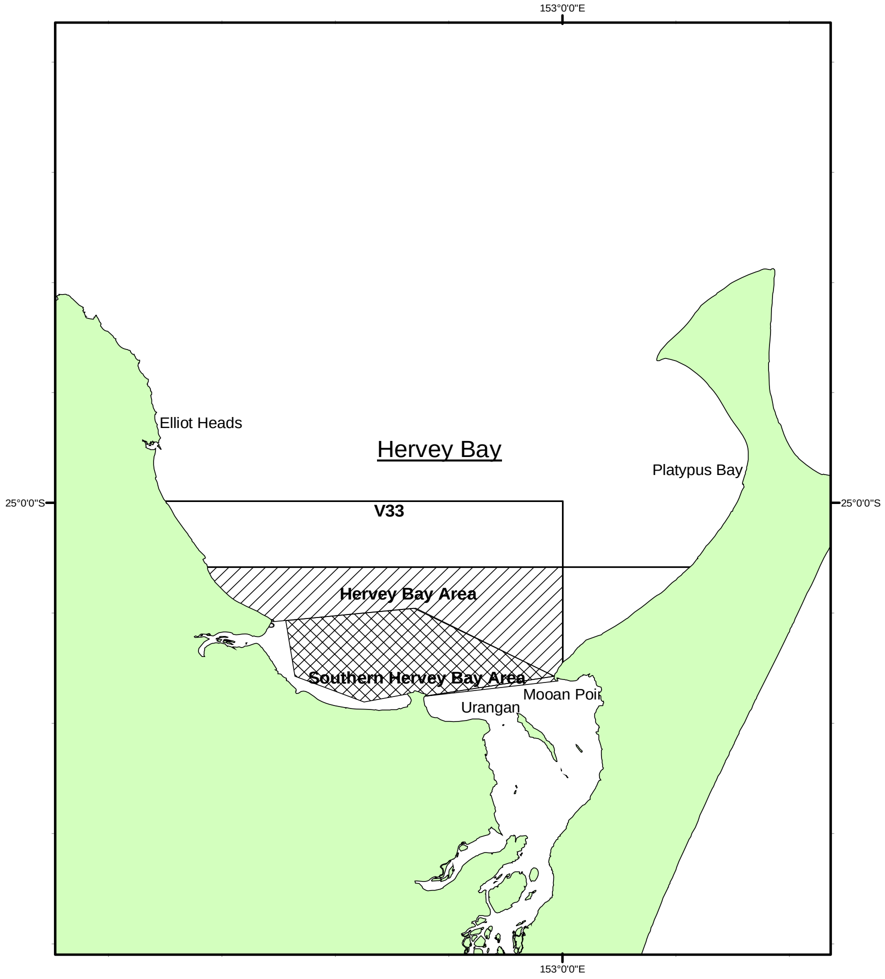


Figure 8.2.1. Chart of Hervey Bay, showing location of the Southern Hervey Bay Trawl Closure (SHBTC) Area (cross-hatched). Also shown are the northern and eastern boundaries of the half-degree Grid V33 and the “inshore” gear-limitation area (hatched).

The original closure was for the period July–September inclusive. This was later extended by one month (into spring) to July–October inclusive, although the Regulatory Impact Statement refers to the extension being for the benefit of anglers during the autumn and winter fishing periods. The test period referred to in the review event is, however, during autumn.

The objectives of this research were to a) determine whether there has been any change in the amount of fishing effort in the closure area during the test period in the last two years, and b) estimate the whiting bycatch of trawlers working in the closure area during the test period. Funding for the work was provided by the Queensland Fisheries Business Group. While the project’s objectives did not initially include an examination of the impacts of trawling on whiting catches in Hervey Bay, the need for this work presented opportunities for the project to further test the effects of TEDs and BRDs (albeit in a relatively minor fishing sector) and to further describe the bycatch in the trawl fishery, which are consistent with the FRDC project’s objectives.

8.3 METHODS

For Objective 1 – to estimate the amount of trawling effort carried out in the closure area before its declaration and to provide an estimate of year-to-year differences – the project required the use of Vessel Monitoring System (VMS) and Commercial Fisheries Information System (CFISH) data. From previous experience it was considered unlikely that there would be a high level of precision in the fishing operation locations reported in CFISH. Because the Southern Hervey Bay closure area accounts for only about 30% of the total fishable area of the CFISH grid (V33) in which it is located, it was recognised that a significant proportion of the CFISH catch records could not be attributed specifically to the area inside or outside the closure. For this reason we considered it necessary to use the spatially explicit VMS data to obtain a more accurate picture of fishing effort in the closure area. However, although the spatial data in VMS are highly reliable and specific, there remains a problem with determining whether the vessel whose position is known accurately was actually engaged in fishing activities at the time.

Estimation of the bycatch of winter whiting (and other species) was approached by conducting a trawl survey in and around the closure area as close as possible to the time span referred to in the Trawl Management Plan. In order to account for the fact that bycatch reduction devices (BRDs) and turtle excluder devices (TEDs) have been introduced into the fishery over the period of interest, and may have contributed to (undocumented) changes in bycatch rates, it was necessary to use such net modifications in the survey. However there was no single design of either BRD or TED in the fishery, and many adaptations which fitted the loose legislated guidelines were developed by different trawler skippers and operators. This meant that we needed to determine whether there was a “most frequently used” design typical of that part of the fleet that worked the southern Hervey Bay area.

VMS and CFISH data were then used in conjunction with the experimental results to provide a gross estimate of total whiting bycatch. The BRD trials also allowed collection of biological material for taxonomic purposes (particularly to determine whether more than one species of whiting was represented in the trawl bycatch), age-growth estimation and estimation of general bycatch levels and composition in an area that had not previously been surveyed.

The fishing vessel *Lewis Venture* (FPPX), skippered by Mr Reg Saunders of Urangan, was chartered to undertake the four-night survey to estimate the catch of winter whiting during the period of interest by a typical inshore trawler, and to determine whether the use of a TED and BRD had any detectable effect on bycatch levels, particularly winter whiting. Twin standard four-fathom, two-seam Florida Flyer nets were used, as this was determined (from interviews with trawl fishers who had registered previous significant catches from the southern Hervey Bay region) to be the most common setup amongst the small trawlers operating in that area. In addition, most of the survey area was within the “gear restriction” area (south of 25°05’ S) where the 8 fm headline-length limit applies. This restricted the number of samples that could be taken simultaneously (which might otherwise have been four in the case of quad gear). All trawling was done at night, the first shot commencing 20 minutes after official sunset, and the last shot lifted not later than 20 minutes before sunrise.

The sampling strategy required four nights of fishing with two nets, one of which was fitted with a TED and the other without. Both were fitted with a closable triangular fisheye BRD installed (Figure 8.3.1. manufactured and supplied by Mr K Wicks), as this appeared to be the most common BRD by the Hervey Bay-based boats. Closure of the fisheye by securing a cover with cable ties effectively created a no-BRD net.

Figure 8.3.1. The fisheye BRD as used by Mr Reg Saunders on the *Lewis Venture* (FPPX). The effects of this device on prawn, whiting and bycatch catch rates were evaluated.

Shot length was specified at 1.0 nautical mile (20 minutes bottom time at ~3 knots; allowing 1 hour for the shoot-drag-retrieve cycle and steam to the next site). Twelve shots per night were scheduled, giving 2 x 12 = 24 samples per night, and 24 x 4 = 96 samples in total. Two nights each were scheduled for inside the closure area (designated South V33) and outside the closure (North V33) (Figure 8.3.2). The order of areas sampled from night to night was Southern Hervey Bay (SHB), North V33, SHB, and North V33.

Comparisons were made between codend treatment types as follows:
TED+BRD compared against Standard net (i.e, no TED or BRD);
TED compared against Standard net;
TED+BRD compared against BRD; and
TED compared against BRD.

Location of nets (i.e. on either the port side or starboard side) remained fixed during any one night. Port and starboard codends were reversed at the end of the second night.

Forty-eight coordinates (24 inside the SHB closure and 24 outside) were chosen randomly (Figure 8.3.2). The sites are identified sequentially from 1 to 48. Before fishing commenced, all the coordinates (with identifying shot numbers) were keyed in to the vessel's plotter. An attempt was made to avoid allocating sites in or close to areas that the vessel's skipper had identified as having hookups or foul ground. To save steaming time and minimise track overlap, trawl tracks were generally directed towards the next site to be occupied. The trawl tracks at each site were recorded (via GPS) on the vessel's plotter and later transferred to diskette.

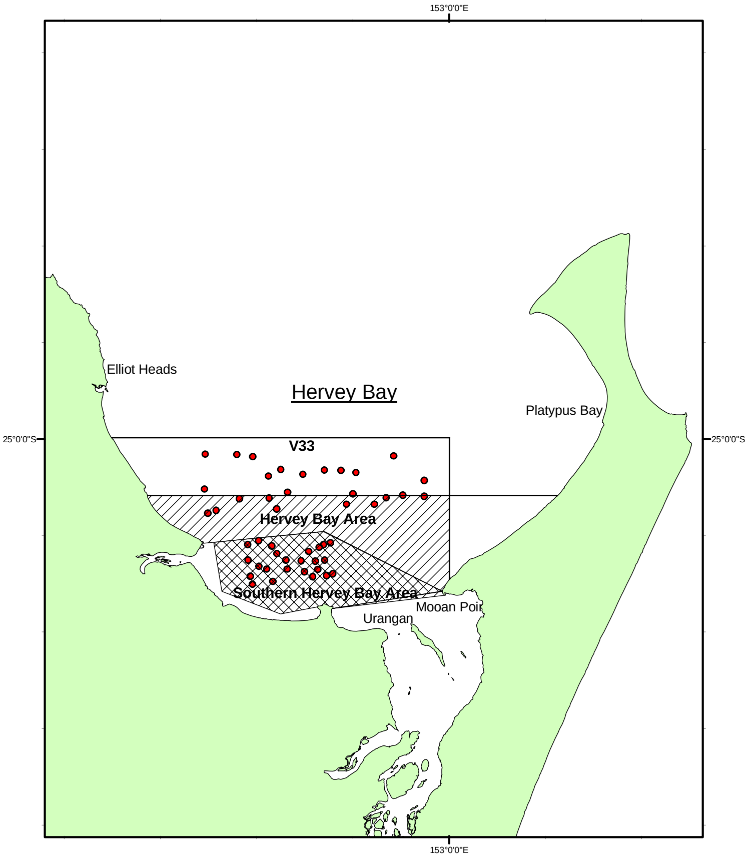


Figure 8.3.2. Location of sampling sites inside and outside the SHBTC area.

The following procedure was adopted for sorting and storing the catch and recording "back deck" data:

- Port and starboard net catches were kept separate on the sorting tray.
- Size and/or weight of any "monsters" and large elasmobranchs (> about 1.5 m for sharks and shovelnose rays; > 80 cm disc width for rays) were estimated. The animals were identified and then released.
- The following were separated out from the catch, and placed in separate buckets or crates:
  - all marketable species of prawns (all sizes)
  - all whiting (all species, all sizes)
  - all legal sized byproduct (blue swimmer crabs, scallops, bugs and squid)
- Cuttlefish, octopus and pinkies were left in the bycatch.
- Byproduct samples were counted and weighed, then released.

- Bycatch was weighed and, if more than 10 kg total, sub-sampled (about 10 kg into a prawn carton) and the remainder discarded. The sub-sample was then bagged, labelled and snap frozen.
- Marketable prawns, whiting and elasmobranchs were weighed, bagged, labelled and snap frozen.

8.4 RESULTS AND DISCUSSION

8.4.1 Estimation of trawling effort from logbook data

A retrieval of all records from the TRAWL database within the period 1 January 1998 to 30 June 2002 and within the bounds of Grid V33 (25.0°–25.5 °S; 152.5°–153.0 °E) was undertaken on 10 January 2002. This process was left as late as possible to ensure that the maximum number of logbooks had been sent to and processed by QFS data entry staff. Despite this, it appears that at the time of retrieval there were still some unprocessed logbook sheets (J Higgs, pers. comm.). This retrieval yielded a total of 9178 records, which comprised 802 fishing operation dates. For any given vessel there may have been more than one fishing operation logged on a particular date, and there were usually multiple records (for different species) per operation number.

8.4.2 Spatial precision in reporting

To find the amount of precise trawl data in CFISH needed to determine whether the operation was inside or outside the closure area, we analysed the data by year and precision code, selecting only data for the period April–May inclusive. In the earlier years (1998 and 1999) more reports were at the half-degree grid level than the six-minute sub-grid level, but subsequently there was an increasing proportion of reports at the sub-grid level (Figure 8.4.1). Very few records in any year were reported at the highest level of precision (lat-long coordinates). This means that for about half the records in Grid V33 it was impossible to tell whether the reported fishing location was inside or outside the closure area.

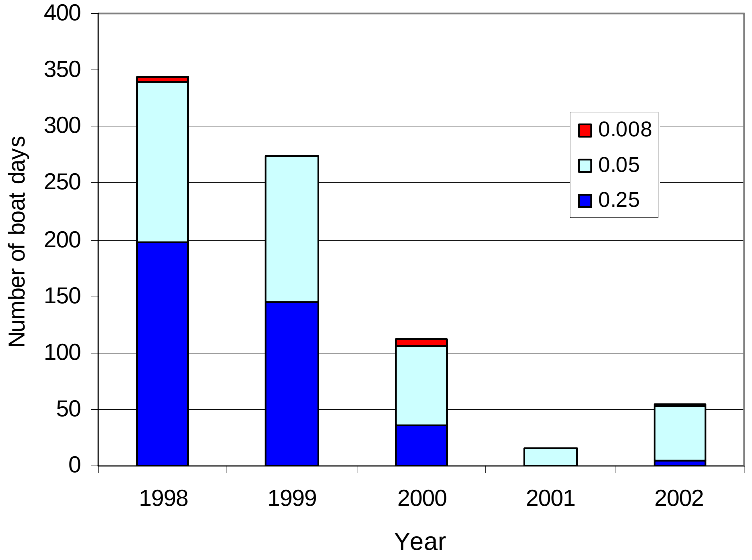


Figure 8.4.1. Number of boat-days in April and May each year on which fishing locations were reported at three levels of spatial precision (0.25: grid; 0.05: sub-grid; 0.008: lat-long) in Grid V33.

To investigate the appropriateness of allocating the low-precision effort (and catch) records proportionately to the sub-grids specified by higher precision reporting levels, we compared the catch composition of the two groups. The principle was that, if the catch compositions were much the same, then there would be no reason to suspect that the catch data were biased in terms of reporting precision level.

The overall species composition (by weight) of the pooled low-precision and high-precision catches were determined, and ranked according to the top 14 species categories in the low precision group (Figure 8.4.2). The rankings of the most important species were quite similar, suggesting that there was a relatively low probability that fishing operations reported at the half-degree grid level of precision were carried out in a substantially different location from those reported at the six-minute (sub-grid) precision level. There was, however, a tendency for vessels reporting at the lowest precision level to list larger catches of unspecified categories such as whiting and crabs.

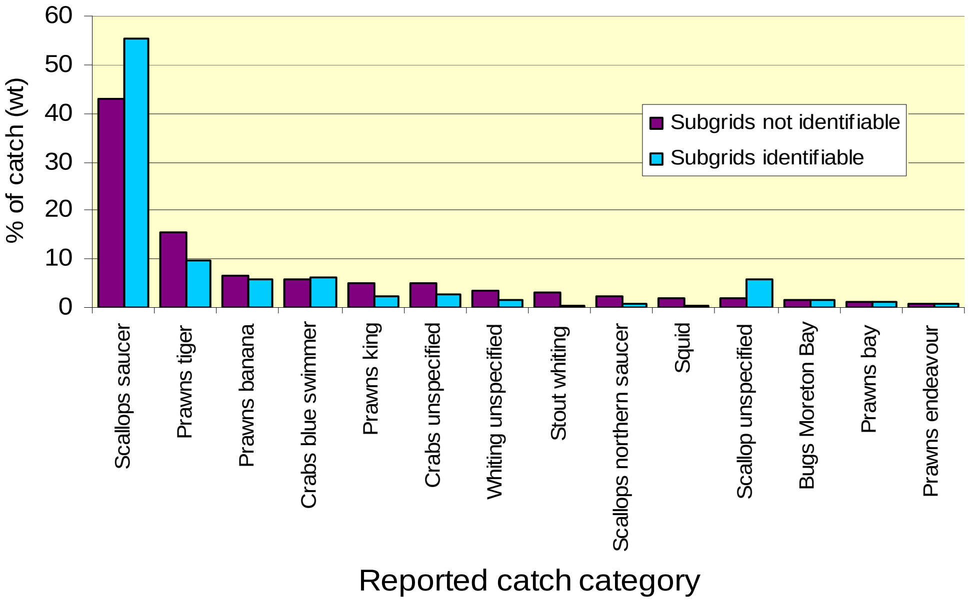


Figure 8.4.2. Comparison of the proportional representation of the 14 most important species in catches from vessels reporting their fishing locations at two levels of precision (30-minute Grid, where sub-grids are not identifiable, and six-minute sub-grid or lat-long, where sub-grids are either specified or derivable.

Some vessels reported in a quasi shot-by-shot manner (i.e. with more than one fishing operation logged in a particular day), but most did not. For this reason it was decided to present CFISH effort statistics in terms of the number of boats and boat-days. Both effort statistics show a clear and significant decline over the five-year period (1998–2002) (Figure 8.4.3). While the number of boats reporting some trawling activity in the closure area varied from five to eight over the same period (Figure 8.4.3, top), the number of days fished in the closure area fell from about 65 in 1998–99 to between 10 and 33 in 2001–02 (Figure 8.4.3, centre). The average number of fishing days per boat in the area declined from around 10 in 1998–99 to about 4 in 2000–02 (Figure 8.4.3, lower).

On the assumption that there was no spatial bias between fishing records reported at high and low precision levels, we allocated the low precision records (for each year separately) either to inside or outside the closure area on the basis of the proportions derived from the high precision (sub-grid level) records (Table 8.4.1).

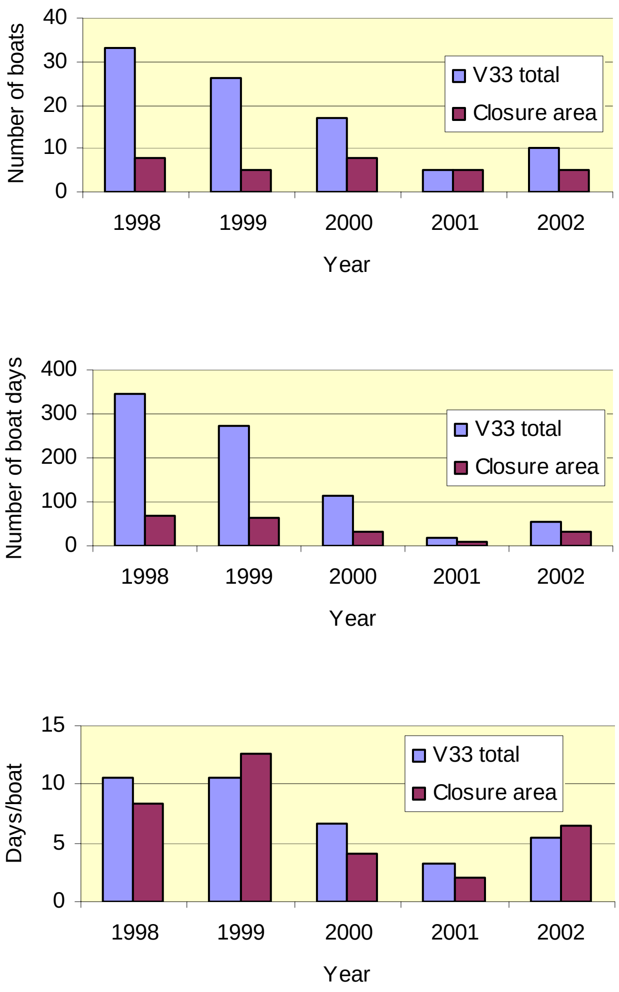


Figure 8.4.3. Comparison of yearly changes in fishing effort (boats and boat-days) between all of Grid V33 and the approximate closure area (i.e. all subgrids falling within or largely within the closure area).

Table 8.4.1. Estimated total effort (boat-days) in Grid V33 by year, inside and outside the SHBTC area, resulting from the proportional allocation of records reported at the lowest level of precision. Records for sub-grids straddling the northern boundary of the SHBTC were allocated on the basis 50% inside and 50% outside the closure area.

In/out SHBTC	**1998**	**1999**	**2000**	**2001**	**2002**	**Grand Total**
Inside	136.1493	132.7519	30.61333	8	30.85714	341.2264
Outside	210.8507	141.2481	81.38667	8	23.14286	461.7736
Total	347	274	112	16	54	803

The change in trawling effort over the five-year period is quite apparent (Figure 8.4.4), which shows a drop from around 140 boat days in 1998–99 to around 20 in 2000–02. The slope of the fitted regression is on the borderline of statistical significance ($P = 0.06$). There was, however, no consistent trend over the three-year period 2000–02.

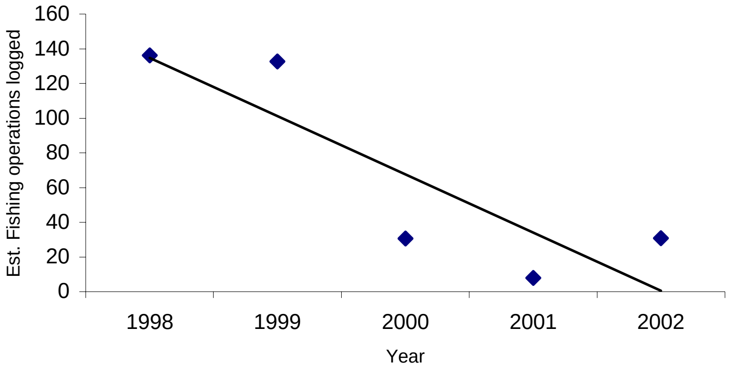


Figure 8.4.4. Trend in estimated trawling effort (boat days) over the period 1998–2002 inside the SHBTC during April and May.

8.4.3 Trends in reported catch of winter whiting

Year-to-year changes in total reported catch of winter whiting and unspecified whiting were derived from the same data set as described above. Table 8.4.2 shows that reported catches of winter whiting (assumed to include "unspecified" whiting) fell from about 1100 to 1500 kg (in 1998 to 2000) to zero in 2001 and 2002. About half of the reported yearly catch was taken in April and May in 1998 and 1999, and about two-thirds in 2000.

Table 8.4.2. Reported winter and unspecified whiting catches (kg) inside the SHBT closure area, by year. Where there are two figures separated by a slash, the first refers to the April–May period and the latter the whole of year.

Category	1998	1999	2000	2001	2002
Whiting unspecified	**563/1119**	**715/1189**	**0**	**0**	**0**
Winter whiting	**0**	**6**	**1175/1589**	**0**	**0**
Total	**563/1119**	**715/1195**	**1175/1589**	**0**	**0**

8.4.4 VMS data

In October 2002 QFS staff carried out a retrieval from the VMS database. The selected data were limited to the months of April and May, and included the closure area within the bounds of 25°08’ to 25°16’ S and 152°38’ to 152°59’ E. In terms of decimal degrees (which is the spatial coordinate format used in the VMS database), this equates to 25.1333° to 25.2667 °S and 152.6333° to 152.9833 °E.

This retrieval produced 2096 records, covering the years 2000–2002 inclusive (no data are available for earlier years). Each record represents one VMS interrogation or poll and generally successive polls (where occurring) were one hour apart.

An algorithm or decision-rule was needed to help decide objectively whether a record referred to a vessel that was engaged in trawling, or to one that was at anchor, in port, or steaming. As the SHBTC is close to the northern entrance to Great Sandy Strait and to the port of Urangan, it is likely that many of the interrogation records would relate to vessels passing through the area on their way into or out of port. They may also relate to vessels at anchor in the SHBTC area, as the vessels' VMS systems remain operational unless deactivation has been formally requested, as may be required if the vessel is undergoing repairs. As most trawling activity takes place at night in the Hervey Bay area, the date field was adjusted on the basis of whether the time of day was before or after noon, such that the fishing day extended from noon on one day to noon on the next. This meant that pre-noon records were attributed to the previous calendar day. The data set contained a "speed" field, which is a value calculated from the spatial and time differences between the current and the previous interrogation. The speed units (m sec^{-1}) were converted to knots (i.e. nautical miles per hour) by multiplying the value by 1.944.

A number of assumptions were made in setting the selection algorithms. Firstly, if a particular vessel was "pinged" only once on a given (fishing) day, it was deemed to have been in transit, regardless of its calculated speed. It is highly unlikely that a vessel could have been fishing for any substantial length of time in the SHBTC and not been interrogated more than once over the 24-hour period. Such data were therefore omitted from the effort estimates. The first pass through the data set removed 607 records of this type (i.e. single pings), leaving 1489, representing vessels that were polled more than once on a given fishing day.

While trawling in the main shipping channel south-east of the fairway buoy is not entirely unknown, it happens very rarely (Noel Riley [QBFP], Reg Saunders pers. comm.). The area surrounding the channels and within the SHBTC are shoal grounds and not trawlable. Although it is actually part of the SHBTC, the triangular area extending from the Fairway Beacon south to Point Vernon then east to Moon Point was therefore considered effectively untrawlable for the purposes of this study. Location records within that area were most likely the result of vessels in transit or at anchor, and were therefore disregarded. This pattern was seen clearly in the cumulative spatial distribution of VMS interrogation coordinates for all vessels (during April and May) over the three-year period. Removal of records from this triangular region left a rectangular area encompassing the trawlable part of the SHBTC from (in decimal degrees) 25.1467° to 25.2500 °S and from 152.6333° to 152.7867 °E. When records were taken just from this area, the data subset reduced to only 416. This suggests that over 1000 records were attributable to vessels in transit to or from Urangan or at anchor in sheltered waters.

The final filter to be applied was calculated speed. In general, the effort management system employed by the QFS is based upon the assumption that a vessel must be travelling faster than 5 knots to be considered steaming (i.e. vessels travelling less than 5 knots are considered trawling. However, because most of the trawlers that work the southern Hervey Bay area tend to be older, smaller boats, it was considered unlikely that a calculated speed in excess of 4 knots would indicate trawling activity. On the other hand, quite low apparent speeds may be generated if the trawl track is curved or if the boat is working a particular 'shot' on successive occasions. Clearly there needed to be a way of deciding whether a boat was not trawling (it might be drifting, or at anchor in a changing tidal flow) but nevertheless registering a non-zero calculated groundspeed. We chose a somewhat arbitrary 0.5 knots as the cut-off point between stationarity and trawling. Of the 416 records from the trawlable area of the SHBTC, 136 had calculated speeds of between 0.5 and 4 knots. Of the remainder, speeds of 4 knots or more were registered 24 times (presumably vessels in transit), and speeds of 0.5 knots or less were registered 256 times (not fishing).

Thus, from the initial data set of 2096 records, only 136 are considered (on the basis of the assumptions and decision-rules above) to relate to actual trawling activity in the SHBTC during April and May over the three-year period 2000–02. The distribution of fishing effort between years (as estimated from the frequency of interrogations) is shown in Table 8.4.3. No detailed spatial information on the distribution of fishing effort is provided in this report due to confidentiality clauses that relate to the reporting of fishing effort from fewer than five vessels.

Table 8.4.3. Number of trawlers considered to have been fishing within the SHBTC (during April and May) each year. The number of (hourly) interrogations may be considered a proxy for trawling effort.

Year	Number of boats	Number of VMS interrogations	Mean number of interrogations per boat
2000	8	77	9.6
2001	2	24	12
2002	3	35	11.7

Application of the same decision-rules consistently across years indicates that, according to the spatially accurate VMS data, there has been a substantial reduction in the number of vessels working in the SHBTC during April and May, from eight in 2000 to three in 2002. It is pertinent to mention that the VMS data become available in “real time”, so there is no backlog of un-entered or unprocessed data. In other words, the 2002 data for April and May were all available when the extract was done. It should also be remembered that the SHBTC is only closed for a certain period each year, and trawling during the months of April and May is quite legitimate.

Not only was there a substantial reduction in the number of boats, the number of (multiple) interrogations declined by about 50% from 77 in 2000 to 35 in 2002. The number of interrogations may be considered a proxy for trawling time, as the probability that a vessel will be interrogated within a certain area is directly proportional to the amount of time it remains in that area.

Despite the quite dramatic change in apparent fishing effort (whether estimated as boats or fishing time) over the three-year period, regression analyses indicated that the change was not statistically significant. This is due a) to the fact that only three data points were able to be compared, and b) to the relatively poor fit between these observed data and the fitted linear regression.

It would appear that, over the three years for which VMS data are available, there has not been any significant change in the average time the vessels spent working in the SHBTC area during April and May. This is deduced from the mean number of pings per vessel, which remained around 10–12 over the three-year period (Table 8.4.3).

8.4.5 Effects of TED and BRD on winter whiting catches

The observed mean catch rates of whiting from the research charter are provided in Table 8.4.4. Mean catch rates varied slightly between codend types, from 0.73 kg nautical mile^{-1} in the standard net to 0.86 kg nautical mile^{-1} in the net with both the TED and the BRD. There was a marked difference between the Southern Hervey Bay Trawl Closure (SHBTC) and the area open to trawling. Catch rates in the closed area were much higher than those in the open area.

Table 8.4.4. Observed mean catch rate of whiting (kg nautical mile^{-1}) from the four net types in each area. Each mean is based on 12 observations (4 nights by 12 trawls towing 2 nets = 96 observations).

Area	Standard net	Net with BRD only	Net with TED only	Net with TED and BRD together
Inside SHBTC	0.73	0.85	0.81	0.86
Outside SHBTC	0.02	0.07	0.0	0.04

An accumulated analysis of variance using a normal distribution and identity link function was undertaken on the transformed whiting catch data (log$_e$ whiting catch rate + 0.01). The area effect was highly significant (*P* <0.001, Table 8.4.5). However, neither the side of boat nor the codend treatment type had a significant effect on the catch rate of whiting. That is, the observed differences in catch rate according to net type are due to external factors rather than the gear used.

Table 8.4.5. Accumulated analysis of variance showing the effects of codend type on whiting catch rate.

Change	d.f.	s.s.	m.s.	v.r.	F pr.
+Area	1	275.835	275.835	134.11	< 0.001
+Side of boat	1	0.036	0.036	0.02	0.895
+Codend treatment type	3	3.634	1.211	0.59	0.624
Residual	90	185.105	2.057		
Total	95	464.61	4.891		

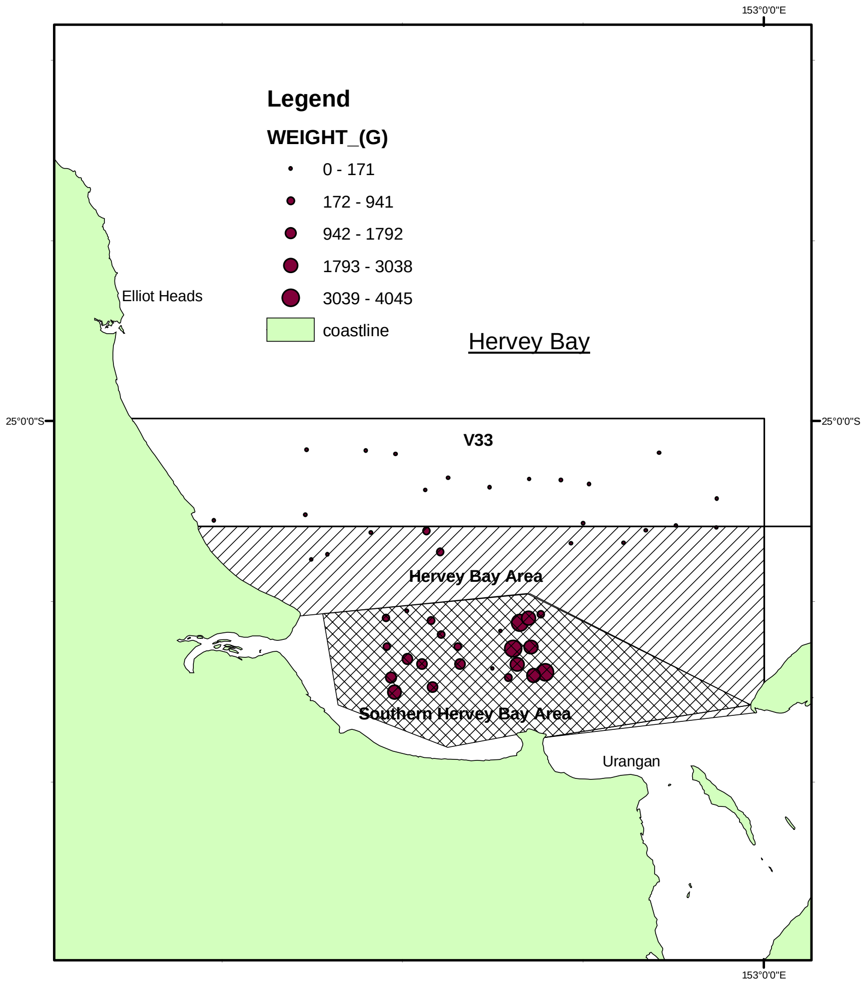


Figure 8.4.5. Distribution of winter whiting *Sillago maculata* catches from the trawl charter. Note the difference in apparent abundance between the area of the SHBTC and that outside.

8.4.6 *Effects of TED and BRD on other bycatch*

The catch rate of non-whiting bycatch is provided in Table 8.4.6. These catch rates exclude monsters (large animals such as turtles, sharks and rays). The incidence of monsters throughout the charter was rare, although one large green turtle weighing approximately 200 kg was caught. The average raw bycatch catch rate varied from 20.65 kg nautical mile^{-1} (in nets with TED and BRD) to 23.91 kg nautical mile^{-1} (in nets with just a TED) (Table 8.4.6). A list of the 186 bycatch species and their total weight recorded during the charter is provided in Appendix 4.

Table 8.4.6. Observed mean catch rate (kg nautical mile^{-1}) of non-whiting bycatch caught in each of the four net types in each area. Each mean based on 12 observations (4 nights by 12 trawls towing 2 nets = 96 observations). Monsters are not included.

Area	Standard net	Net with BRD only	Net with TED only	Net with TED and BRD together
Inside SHBTC	20.85	21.27	22.75	20.65
Outside SHBTC	25.79	22.64	23.91	22.38

In all codend treatment types the raw catch rate of bycatch species was slightly higher outside the closure area than inside (Table 8.4.6), however, the area term was not statistically significant and therefore not included in the final model (Table 8.4.7). There was a significant difference in catch rate among the various trawl shot locations (sites), and between the port and starboard sides of the vessel. The port side had higher catch rates, possibly due to subtle differences in the way the nets were hung or the way the otter boards towed. Interestingly, there was no significant effect of codend treatment type (i.e., presence or absence of TED and/or BRD) on the catch rate of the total bycatch.

An accumulated analysis of variance using a normal distribution and identity link function was undertaken on the transformed bycatch catch rate data [$\log_e$ (bycatch catch rate) + 1]. The significance of the effects of location, side of boat and net type on the bycatch are shown in Table 8.4.7.

Table 8.4.7. Accumulated analysis of variance showing the effects of the net type on bycatch catch rate.

Change	d.f.	s.s.	m.s.	v.r.	F pr.
+Site	47	10.48119	0.223	13.54	<.001
+Side of boat	1	0.40334	0.40334	24.5	<.001
+Codend treatment type	3	0.03909	0.01303	0.79	0.505
Residual	44	0.7245	0.01647		
Total	95	11.64812	0.12261		

8.4.7 Effects on prawn catch rates

Tiger prawns were the predominant prawn species caught in the area. Catch rates varied between 0.30 kg nautical mile^{-1} and 0.06 kg nautical mile^{-1} for the different net types and areas (Table 8.4.8) and were higher in the SHBTC.

Table 8.4.8. Observed mean catch rate of tiger prawns (kg nautical mile^{-1}) from the four types of codend in each area. Each mean based on 12 observations (4 nights by 12 trawls towing 2 nets = 96 observations).

Area	Standard net	Net with BRD	Net with TED	Net with TED + BRD
Inside SHBTC	0.23	0.25	0.30	0.24
Outside SHBTC	0.06	0.06	0.14	0.07

An accumulated analysis of variance using a normal distribution and identity link function was undertaken on the transformed prawn catch rate data ($\log_e$ prawn catch rate + 0.01). The catch rate of tiger prawns was significantly higher inside the SHBTC than outside (Table 8.4.9). However neither codend type nor the side of boat affected prawn catch rates.

Table 8.4.9. Accumulated analysis of variance showing the effects of the codend type on tiger prawn catch rate.

Change	d.f.	s.s.	m.s.	v.r.	F pr.
+Area	1	57.794	57.794	34.53	<.001
+Codend treatment type	3	6.912	2.304	1.38	0.255
Residual	91	152.309	1.674		
Total	95	217.015	2.284		

8.4.8 Size-frequency distribution of winter whiting catch

The size-frequency of all *Sillago maculata* taken in all trawl shots during the charter survey is shown in Figure 8.4.6. The modal length (210 mm Fork Length) was somewhat greater (by about 20 mm) than that reported in Weng's 1990–91 study in Moreton Bay at the equivalent time (May–June).

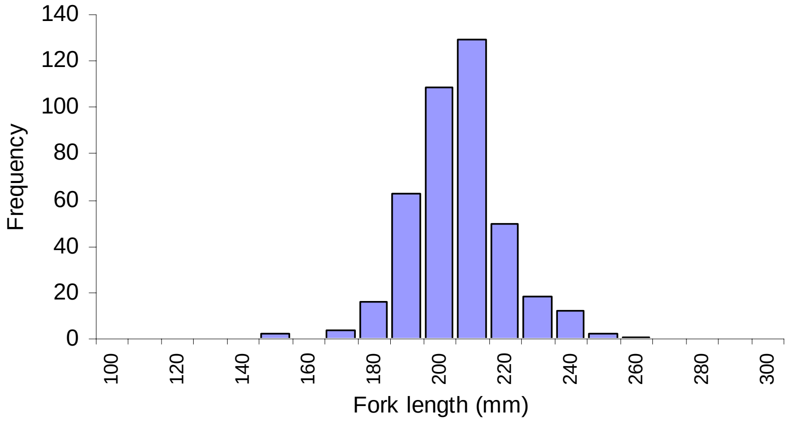


Figure 8.4.6. Length-frequency distribution of winter whiting *(Sillago maculata)* from the trawl survey. Note that as all winter whiting were retained (rather than sub-sampled), this represents the sum total of all of this species taken in the course of 48 x 1 nautical mile trawl shots with two nets.

The frequency distribution was unimodal, suggesting that either the earlier age classes were absent from the study area in Grid V33, or the selectivity of the trawl gear was such as to allow fish smaller than 18 cm to escape through the meshes.

Analyses of the effects of codend treatment type indicate that it is unlikely that the total biomass of winter whiting was affected by the presence or otherwise of the TED or the BRD. There is a possibility that these devices may have had some effect on the size composition of the whiting bycatch, but this has not yet been tested. It is also possible that there is some size segregation between shallower and deeper trawl sites, but this likewise has not been examined.

8.4.9 Estimation of changes in winter whiting bycatch

The CFISH logbook data showed that there has been a marked reduction in the number of fishing operations during April and May in the whole of Grid V33 over the period 1998 to 2002. Because of the high proportion of CFISH records in which the level of spatial precision did not allow effort or catch to be attributed directly to the area inside or outside the SHBTC, the allocation was done on a proportional basis. As a result of this process, total effort in the closure area during April and May was estimated in each of the five years from 1998 to 2002. There was a marked decline over this period, although of only marginal statistical significance. There was no evidence of a consistent decrease in whiting catch over the latter three years of this period (2000–02).

Actual reports of whiting catches (winter whiting and unspecified whiting combined) indicated levels of catch in the first two years of the five-year period of slightly over 1.0 t in the closure area (almost all reported as unspecified whiting), and about 1.5 t in the year 2000 (all reported as winter whiting). There were no reports of either of these categories in the closure area (during April and May) in either 2001 or 2002. It is likely that the 2002 data are incomplete on the CFISH database, but even so, because winter whiting were removed from the permitted species list in October 2000, this is not entirely surprising.

The VMS data, while exceedingly accurate and precise in terms of interrogation position (in contrast to the CFISH data), were difficult to interpret. One of the main reasons related to the proximity of the study area to a major port, and the associated likelihood that a great number of the interrogation records would relate to vessels that were in transit rather than actually fishing. By applying a number of decision-rules the large initial data set was filtered objectively to a relatively small subset of records which probably (though certainly not definitely) related to vessels in the process of fishing. From this three-year subset (the first VMS data came online in the year 2000) we deduce that there has been a decrease in the level of fishing effort between 2000 and 2002. However, the linear regression fitted through these (three) points was not statistically significant. It is of interest that the pattern of fishing effort between the three years was similar for the CFISH and VMS data, even though they are quite distinct measures of effort.

The independent survey, using trawl gear and configurations consistent with those employed by commercial vessels in the area, showed that winter whiting abundance (at least at the time of the survey) was considerably greater inside the closure area than outside (and within the bounds of Grid V33). Bycatch reduction devices and turtle excluding devices typical of those in use by the local fleet had no effect of the catch (weight) of winter whiting. This indicates that (in all probability) the introduction of these devices has had little ameliorating effect on winter whiting mortality levels.

The removal of winter whiting from the permitted species list (in 2000) has led to a substantial reduction in the retention of this species for sale, and has certainly resulted in a complete absence of reported catches in subsequent years.

Assuming that (as a result of the regulation change in 2000) no vessels were actually targeting winter whiting in the subsequent years, the change in whiting catch in the closure area would be due simply to changes in effort. Again assuming that the mean catch rate (0.81 kg of winter whiting per nautical mile) inside the SHBTC (from the trawl survey) applied right throughout the April–May period, and that the number of VMS interrogations (Table 8.4.3) is a measure of fishing time, the catch of whiting could be approximated as follows:

1 hour of trawling at 3.5 knots = 3.5 nautical miles
3.5 x 0.81 = 2.835 kg whiting per hour per net
2 x 2.835 = 5.67 per (2-net) rig per hour

Thus the estimated annual April–May catches in the SHBTC (based on the VMS data in Table 8.4.3) over the three-year period would be :

2000: 77 x 5.67 = 437 kg
2001: 24 x 5.67 = 136 kg
2002: 35 x 5.67 = 198 kg

The figure for the year 2000 (437 kg) is only about 40% of that derived from the logbook reports for the same year (1175 kg). If the reported figure for 2000 is assumed to be correct, the figures for 2001 and 2002 could be pro-rated up to 340 kg and 495 kg respectively.

However, these minor adjustments do not significantly alter the main findings that over the period from 2000 to 2002 it seems highly likely that there has been a reduction in fishing effort, and almost certainly a substantial reduction in the bycatch of winter whiting. This is more attributable to the removal of winter whiting from the permitted species list than to the introduction and uptake of bycatch reduction devices in this component of the trawl fishery.

9 Evaluating the effects of a turtle excluder device (TED) and square mesh codend bycatch reduction device (BRD) in Queensland's deepwater eastern king prawn (*Penaeus plebejus*) trawl fishery

A. J. Courtney, M. J. Campbell, M. L. Tonks D. P. Roy, S. W. Gaddes, P. M. Kyne and K. E. Chilcott

9.1 ABSTRACT

This chapter described the bycatch and quantified the effects of a turtle excluder device (TED) and square mesh codend bycatch reduction device (BRD) on the catch rates of bycatch and targeted prawns in the deepwater eastern king prawn fishery off the south-east Queensland coast, based on a 10-day research charter. A total of 227 taxa were recoded in the bycatch from the charter. Dominant species were gurnards, flatheads, sandpaper fish, hermit and charybdid crabs, sand dollars (Echinoids; *Peronella* sp.), dragonets, snipefish, carids and lizardfish. Bycatch rates were low (1.19 kg ha^{-1} from the standard net) compared to the shallow water eastern king prawn fishery (Chapter 5), mainly because of the greater depths (110–165 m) trawled. When the TED and square mesh codend BRD were used together the mean bycatch rate declined significantly by 29% compared to the standard net, with no effect on the targeted prawn catch rate. Mean catch rates of the commercially important lobster *Ibacus chacei* (Balmain bugs) were significantly reduced by the TED. Large statistically significant reductions were demonstrated for several species when both devices were installed in the net, including the dumpling squid *Euprymna tasmanica* (87% reduction), snipefish *Macrorhamphosus scolopax* (80% reduction), sandpaper fish *Aulotrachichthys* sp. (77% reduction), carid *Plesionika laurentae* (66% reduction) and flathead *Ratabulus diversidens* (45% reduction), with most of these reductions largely attributed to the square mesh codend BRD. Multidimensional scaling and analysis of similarities showed that the bycatch community structure varied with latitude and depth, but not with codend treatment type. Based on the results, we recommend that fishers adopt square mesh codends in the deepwater eastern king prawn fishery as a highly effective BRD that results in no loss of the targeted prawns.

9.2 INTRODUCTION

The eastern king prawn fishery is one of the largest sectors of the Queensland East Coast Trawl Fishery. In recent years the reported catch and effort directed at the sector have increased and it is currently the single most valuable fished species in Queensland, generating about $30 million annually. Eastern king prawns are the largest endemic Australian penaeid prawn and can undertake significant migrations which can exceed 1000 km, generally in a northerly direction. As such the fishery extends over a very large geographic range, further offshore and to greater depths (300–350 m) than most other Australian penaeid prawn fisheries.

In Queensland, management measures for the eastern king prawn fishery include seasonal closures and gear restrictions that are based on depth (i.e., waters that are either less than or greater than 50 fathoms, fm) and reflect the large spatial variation in size and age classes. Trawl nets that operators can use in depths greater than 50 fm (about 91 m) are large, up to 184 m total length or about 92 m head rope length. The catch rate of bycatch in prawn trawl fisheries reduces with depth (see Stobutzki et al., 2001) and so the amount of bycatch produced in the deepwater and its composition are likely to differ significantly from the shallow water fishery. Furthermore, the size of the prawns in the deepwater (> 50 fm) is generally much larger than in the shallow water (< 50 fm). All of these biological and management characteristics should be considered when developing appropriate bycatch reduction devices for the fishery.

Chapter 5 presented results from a research charter conducted in the shallow water eastern king prawn fishery in October 2001 that examined the effects of a radial escape section BRD and TED. When used together the devices were effective at reducing large amounts of demersal and pelagic finfish with fusiform body shape, which comprised a large component of the bycatch. In this chapter we present results from a research charter conducted in the deepwater sector of the fishery that evaluated a square mesh codend BRD that was tested in conjunction with a TED. We chose to test a square mesh codend because previous research in the deepwater fishery had shown that the size of the finfish bycatch is generally smaller than the size of the large targeted adult eastern king prawns. As such, we suspected that a square mesh codend BRD would be effective at facilitating the escapement of many of the small fish species while retaining the large prawns.

9.3 METHODS

9.3.1 Research charter and codend treatments

The square mesh codend BRD and TED were evaluated by undertaking the project’s third research charter in July 2002 in the deepwater (greater than > 50 fathoms) eastern king prawn fishery aboard the commercial trawler, FV *Elizabeth G*, over 10 nights. The charter was conducted in the area between Noosa and Southport, in depths from 60 to 90 fathoms (110–165 m). Trawling was undertaken on known trawl tracks obtained from commercial vessels and located in areas that traditionally receive relatively high levels of effort in July, based on analysis of logbook data. This reduced the chance of hook-ups and ensured that the samples were from areas that were representative of commercial fishing areas (Figure 9.3.1).

Each trawl was two nautical miles in length and along a relatively straight track to ensure that both outside nets swept similar areas along the bottom. Although there is considerable effort in the northern area of the fishery (i.e., around the Swain Reefs region), it was deemed too costly to steam the vessel from the port of Scarborough to the Swain Reefs and return (rather than spend the fuel and time trawl sampling) and therefore sampling was limited to the area between Noosa and Southport.

Three 12-fathom, two-seam Florida Flyers were used in triple-gear configuration with different combinations of the TED and square mesh codend BRD tested in the two outside nets (port and starboard) on each trawl shot. Because the middle net is likely to fish differently from the port and starboard nets, it was not included in the design or the results (although catches from the middle net were measured along with the port and starboard nets).

The square mesh codend BRD (Figure 9.3.2) was constructed out of 3 mm braided polyethylene with a mesh size of 47 mm (17/8 inch). The square mesh section was 66 bars round and 76 bars long. It was sewn onto the aft edge of a diamond mesh codend that was constructed from 45 mm (1¾ inch) 48-ply polyethylene that was 100 meshes round and 60 meshes long. A small section of diamond mesh, 100 meshes round and 3 meshes long, was sewn to the aft edge of the square mesh section so that the drawstrings could be attached in the normal manner. A length of 12 mm polyethylene rope was selvedged along two sides of the square mesh section to take the weight of the accumulated catch, thereby reducing any distortion of the mesh and knot slippage.

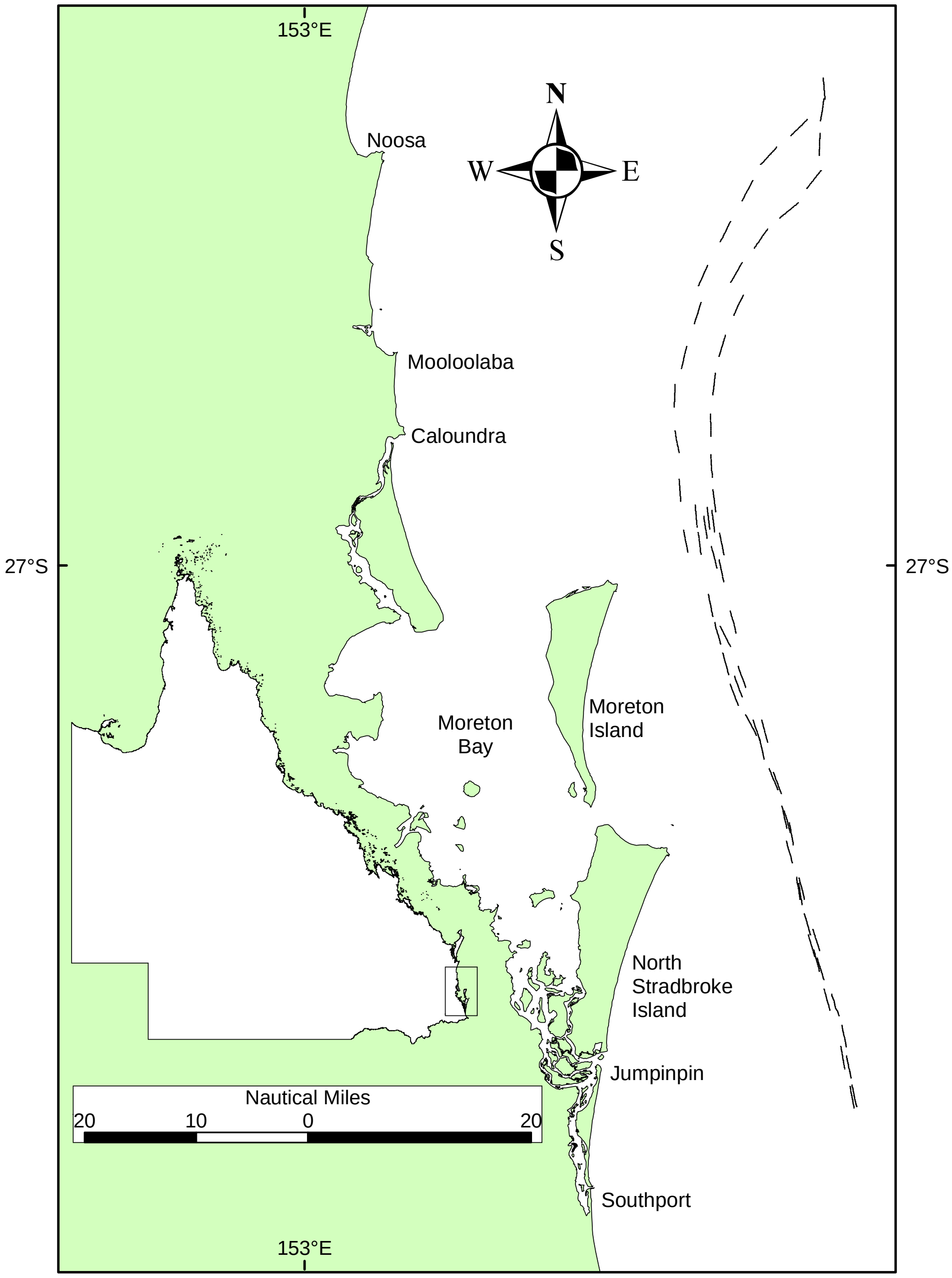


Figure 9.3.1. Location of the 65 two-nautical mile trawls undertaken during the 10-night charter in July 2002. Depths ranged from 60 to 90 fathoms (110–165 m).

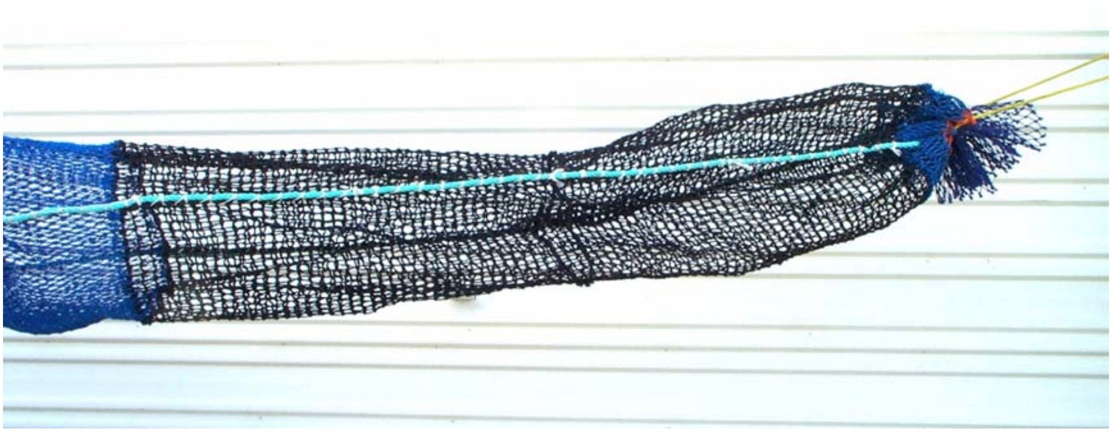


Figure 9.3.2. The square mesh codend BRD that was evaluated during the deepwater eastern king prawn charter was constructed from 17/8 inch black braided polyethylene. The square mesh section was 66 bars round and 76 bars long. Note that a short section of diamond mesh was added to the aft edge of the square mesh so that the drawstrings could be attached in the normal manner. The rope was added to reduce knot slippage.

The TED used throughout the survey was a modified Wick's TED, popular in south-east Queensland. The grid was 69 cm wide and 84 cm high, with a bar-space of 12 cm, sewn into a codend extension at 52^{o}. The standard codend was constructed from 45 mm (1¾ inch), 48-ply polyethylene and was 100 meshes long by 100 meshes round.

Sixty-five sites were trawled over 10 nights. Trawl speed was approximately 2.1 knots, with average trawl duration being 57 minutes. At the completion of each shot, a different combination of codend types was sewn onto the port and starboard nets, based on a predetermined sampling design protocol. This ensured that each combination of codend treatments was tested on both sides of the vessel with equal or very similar replication. The number of times each codend type was trawled is provided in Table 9.3.1.

Table 9.3.1. The number of times each codend type was sampled during the deepwater eastern king prawn charter.

Codend Type	Number of shots
Standard codend	32
Square mesh codend only	32
Modified Wick's TED only	33
Modified Wick's TED and Square mesh codend together	33

9.3.2 Measuring and sampling the catch

Methods for weighing and sorting the catch, obtaining a sub-sample of the bycatch from each net and estimating catch rates are the same as those described in Chapter 5, section 5.3.3. All prawns and byproduct species including Balmain bugs, cuttlefish, pinkies (nemipterid fish) and octopus were retained for later analysis in the laboratory. If the bycatch from each net did not exceed 10 kg, then it was completely retained for later analysis. However, if more than 10 kg of bycatch was caught, then a maximum 10 kg sub-sample was retained.

9.3.3 Statistical design and analysis

The sampling design and statistical methods used for analysing the data were very similar to those described for the shallow water eastern king prawn charter (Chapter 5, section 5.3.5). Because only two of the three nets were sampled at each site simultaneously an incomplete block design (Montgomery, 1997) was applied, with site as a blocking term. Generalised linear modelling (GLM) using GenStat (2005) statistical software was used to examine the variation in catch rates of bycatch (both total bycatch and individual bycatch species) and marketable eastern king prawns, and variation in the mean length of bycatch species. Models took the following general form:

$$U = \beta_o + \beta_1(\text{Trawl site}_{1-65}) + \beta_2(\text{Net position}_{1-2}) + \beta_3(\text{Codend type}_{1-4}) + \varepsilon$$

where U was the predicted mean catch rate of bycatch weight, individual bycatch species weight or marketable prawns, or length of a bycatch species, n was the number of sites trawled, $\boldsymbol{\beta}_o$ and $\boldsymbol{\beta}_2$ were scalar parameters that were estimated, and $\boldsymbol{\beta}_1$ and $\boldsymbol{\beta}_3$ were vector parameters that were estimated and ε was the error term. Only estimates of $\boldsymbol{\beta}_3$ are presented as this parameter quantifies the effects of the different codend types. For purposes of interpretation, the $\boldsymbol{\beta}_3$ parameter estimates were proportionally scaled so that they could be compared against a standard codend parameter value of 1.0. Effects on the mean length of bycatch species were examined using the methods described in Chapter 5, section 5.3.5.

Multidimensional scaling (MDS) was used to examine variation in the bycatch community structure due to latitude, depth and codend type. The statistical software package PRIMER (Plymouth Routines in Multivariate Ecological Research) by Clarke and Warrick (1994), was used to undertake the analyses. A Bray-Curtis similarity matrix (Bray and Curtis, 1957) was used to examine the similarity between each pair of samples and based on standardised catch rates of individual species in each sample (grams per hectare; g ha^{-1}). Further details of MDS methods are provided in Chapter 5, section 5.3.5. To reduce the number of factor levels, depths were rounded to the nearest 10 m and latitude to the nearest 0.5 degree.

9.3.4 Bycatch species catch rates and statistical power

Power analysis was undertaken using the mean predicted catch rates of the bycatch species and the variance estimates derived from the generalised linear models. This was undertaken to determine whether changes in bycatch species catch rates could be detected if a bycatch monitoring program was implemented. The same methods and possible monitoring program scenarios (i.e., 30 trawls and 300 trawls) that were used to undertake the power analysis in Chapter 6, section 6.3.5 were applied.

9.4 RESULTS

9.4.1 Effects on bycatch and prawn catch rates

The observed mean bycatch catch rate from the standard codend was 1.19 kg ha^{-1} (Table 9.4.1). When the square mesh codend BRD and TED were used together the bycatch catch rate fell significantly by 29% ($\boldsymbol{\beta}_3$ estimate of 0.71, $P < 0.01$, Table

9.4.1). Most of the reduction in bycatch was due to the square mesh codend ($\boldsymbol{\beta}_3$ estimate of 0.82, Table 9.4.1), as the TED by itself had no significant effect ($\boldsymbol{\beta}_3$ estimate of 1.03, Table 9.4.1).

Over the 10 nights, 4685 eastern king prawns were caught with a mean carapace length of 42 mm, which equates to a U/11 count prawn. The carapace lengths ranged from 27 mm (U/38 count) to 72 mm (U/2 count). Codend types had no significant effect on the mean catch rate of prawns (Table 9.4.1) or their length-frequency distributions (Figure 9.4.1), compared to the standard net. Mean prawn size was the same (42 mm CL) for all codend types. Note that because the charter was conducted in deepwater (i.e., 110–165 m) there were no small prawns caught – all size classes were relatively large and marketable.

Table 9.4.1. Effects of codend type on the catch rates of bycatch and eastern king prawns based on 130 measures (65 sites trawled x 2 nets). Generalised linear modelling was used to quantify the effects. Significant differences between codends (*P* < 0.05) are bolded and identified by different alphabetic characters (A, B, C or D). Parameter estimates were proportionally scaled so they can be compared to a standard net parameter value of 1. Standard errors in brackets.

Catch component	**Mean observed catch rate (kg ha^{-1}) in Standard net**	**Predicted change in catch rates based on generalised linear model parameter estimates (proportionally scaled to a Standard net parameter value of 1)**			**Distribution type**
		TED only	**Square mesh codend BRD only**	**Square mesh codend BRD and TED together**	
Marketable prawns (i.e., all prawns)	0.25 (0.03) A	1.06 (0.02) A	1.00 (0.02) A	0.97 (0.02) A	N (Sqrt)
Total Bycatch	**1.19 (0.22) A**	**1.03 (0.10) A**	**0.82 (0.08) B**	**0.71 (0.07) B**	**Gamma**

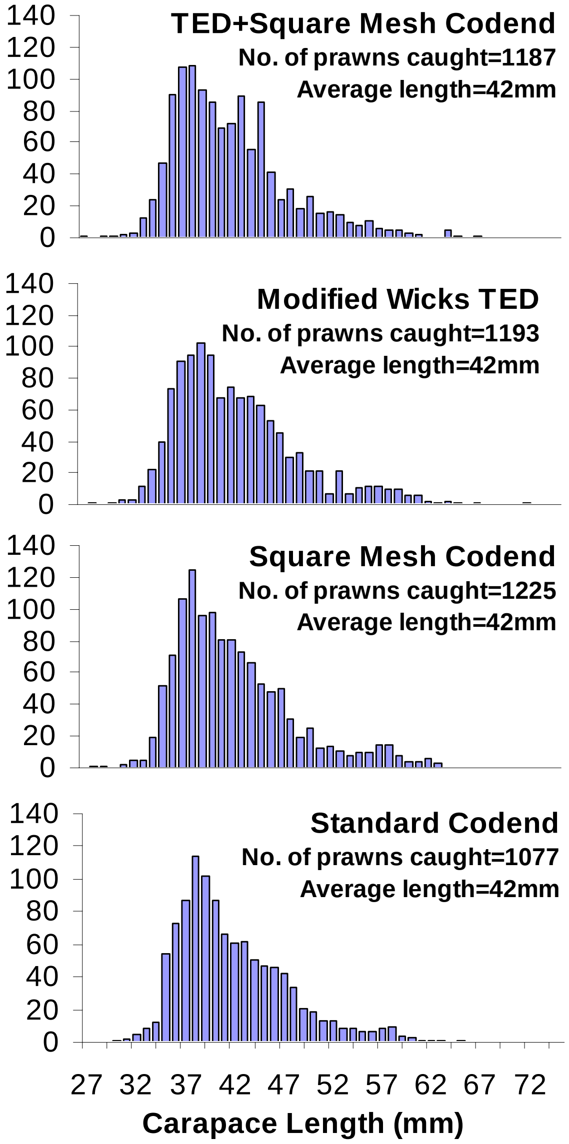


Figure 9.4.1 Carapace length frequency distributions for prawns caught in each codend type during the deepwater eastern king prawn charter. There was no significant difference in the catch rate or size frequency of prawns caught between the four codend types. Each codend type had the same average prawn size.

*9.4.2 Effects on Balmain bugs (*Ibacus *spp.)*

Generalised linear modelling was carried out, using a Poisson distribution and logarithm link function, on the catch rate of Balmain bugs *Ibacus chacei* caught during the charter. While this species is not targeted by the fleet, it is a commercially valuable byproduct of the eastern king prawn fishery. The Wick's TED reduced the catch rate of Balmain bugs significantly compared to the standard net and the square mesh codend. There was no significant difference in the catch rates of Balmain bugs between the square mesh codend and the standard net, nor was there a significant difference between the square mesh codend and TED combination and the standard net. Further, the different combinations of TEDs and BRDs had no significant effect on the catch rate of cuttlefish, which are another important byproduct (i.e., permitted species) of the fishery.

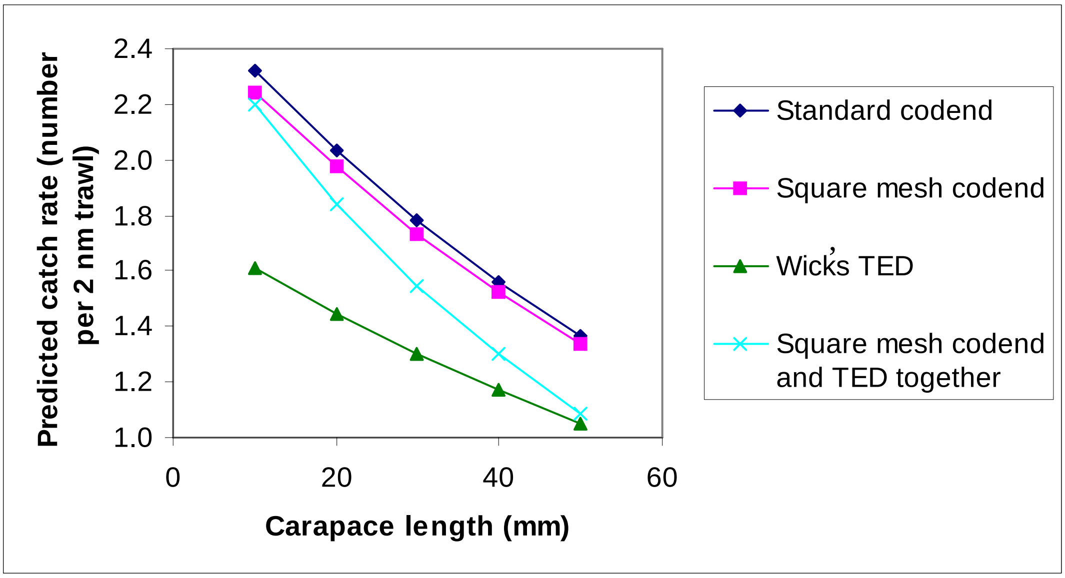


Figure 9.4.2. Predicted catch rates of Balmain bugs *I. chacei* per two nautical mile trawl based on 130 (65 sites x 2 nets) observations obtained during the deepwater eastern king prawn charter. Codends with the TED significantly reduced catch rates, particularly for the larger size classes.

9.4.3 Effects on individual bycatch species

A total of 227 taxa were recorded in the charter bycatch. Seven taxa made up 50% of the bycatch weight and 40 taxa made up 90%. The three-spined cardinal fish (*Apogonops anomalus*) was the most dominant species by weight and comprised 13.5% of the bycatch, followed by the orange-freckled flathead (*Ratabulus diversidens*, 10.4%), the gurnard (*Lepidotrigla argus*, 8.5%), the orangemouth lizardfish (*Saurida filamentosa*, 5.7%), the Queensland stinkfish (*Callionymus moretonensis*, 3.9%), whitefin trevally (*Carangoides equula*, 3.6%) and the yellow-lip threadfin bream (*Nemipterus aurifilum*, 3.6%).

A complete list of 346 taxa that the project recorded in bycatch from the deepwater eastern king prawn fishery, and their catch rates, is provided in Appendix 5. The list includes the 227 species recorded from the research charter and additional species that were recorded in samples obtained opportunistically from vessels operating the sector.

Most species in the bycatch from the research charter were relatively rare or uncommon in the bycatch. For example, 70% of species (159 taxa) were present in fewer than 10% of samples. Only 12 taxa were present in more than 50% of samples and 66 taxa were present in only one bycatch sample. Because of the high zero counts, analyses of codend type effects on catch rates were limited to the more common species. Analyses were carried out on 40 taxa that comprised 90% of the weight of bycatch from the standard net, and of these 15 (38%) species experienced a significant reduction in catch rate due to the TED, square mesh codend BRD or both (Table 9.4.2). The largest reduction (i.e., 87%) was achieved for the southern dumpling squid *Euprymna tasmanica* ($\boldsymbol{\beta}_3$ estimate of 0.13, Table 9.4.2), which was almost entirely excluded by the square mesh codend. The snipe fish *Macrorhamphosus scolopax* had the second largest reduction of 80% ($\boldsymbol{\beta}_3$ estimate of 0.20, Table 9.4.2) followed by a 77% reduction for the sandpaper fish *Aulotrachichthys* sp. ($\boldsymbol{\beta}_3$ estimate of 0.20, Table 9.4.2) – both of which were largely due to the square mesh codend. In general, the TED had relatively little effect with the exception of the orange-freckled flathead *R. diversidens*, where the TED (by itself) reduced catch rates by 43% and the square mesh codend reduced catch rates by 26%.

9.4.4 Effects on mean length of bycatch species

The codend effects on mean length were examined for 40 species (Table 9.4.3). Sixteen species were found to have a significant change in mean length due to the TED, square mesh codend BRD or both. In nets with the square mesh codend and TED together, an increase in mean size was obtained for 13 of the 16 species. The largest predicted increase was obtained for the beaked salmon *Gonorynchus greyi*, which increased from a mean length of 211.90 mm in the standard net to 281.50 mm in the net with the square mesh codend. In general, the analyses indicated that a) many of the small individuals escaped via the large square meshes, resulting in an increase in mean size of those retained in the codends, and b) the TED had relatively little impact on mean size.

Table 9.4.2. Effects of codend type on the catch rates of the commonly encountered bycatch species in the deepwater eastern king prawn fishery based on 130 bycatch sub-samples (65 sites trawled x 2 nets). Generalised linear modelling was used to quantify the effects. Significant differences between codends ($P < 0.05$) are bolded and identified by different alphabetic characters (A, B, C or D). Parameter estimates were proportionally scaled so they could be compared to a standard net parameter value of 1. Values for the binomial data (B) are probabilities of capture. Standard errors in parentheses.

Species	Occurrence (%) in 130 sub-samples (65 trawls x 2 nets)	Mean observed catch rate (g ha^{-1}) Standard net	Predicted probability of capture in Standard net	Change in catch rates based on generalised linear model predictions			Distribution type
				TED only	Square mesh codend BRD only	TED with Square mesh codend BRD together	
Lepidotrigla argus	87	88.34 (26.30)	*	1.31 (0.20)	1.01 (0.18)	0.73 (0.12)	G
Ratabulus diversidens	**85**	**118.62 (24.56) A**	*****	**0.57 (0.14) B**	**0.74 (0.19) AB**	**0.55 (0.14) B**	**N(log)**
Calliactus sp.	70	6.89 (1.63)	*	0.55 (0.21)	0.69 (0.30)	0.47 (0.18)	G
Charybdis bimaculata	69	16.66 (6.68)	*	1.04 (0.26)	0.87 (0.20)	0.90 (0.22)	G
Dardanus arrosor	64	10.72 (3.22)	*	0.27 (0.18)	0.44 (0.29)	0.30 (0.20)	G
Peronella sp.	56	*	0.61 (0.02)	0.51 (0.03)	0.54 (0.05)	0.57 (0.03)	B
Callionymus moretonensis	52	51.62 (21.61)	*	0.52 (0.19)	0.65 (0.25)	0.49 (0.18)	N(log)
***Aulotrachichthys* sp.**	**51**	**5.55 (1.49) A**	*****	**1.54 (0.47) A**	**0.28 (0.08) B**	**0.23 (0.07) B**	**N(log)**
Macrorhamphosus scolopax	**51**	**18.30 (8.03) A**	*****	**0.88 (0.22) A**	**0.21 (0.05) B**	**0.20 (0.06) B**	**G**
Plesionika laurentae	**50**	**17.58 (6.72) A**	*****	**0.67 (0.15) AB**	**0.43 (0.09) BC**	**0.34 (0.07) C**	**N(log)**
Kempina mikado	46	13.96 (3.46)	*	1.43 (0.52)	0.97 (0.32)	0.63 (0.28)	G
Solenocera choprai	43	13.59 (5.49)	*	1.02 (0.34)	0.90 (0.25)	0.68 (0.25)	G
Saurida filamentosa	**39**	*****	**0.38 (0.05) A**	**0.51 (0.03) B**	**0.32 (0.06) A**	**0.27 (0.05) A**	**B**
Aulopus curtirostris	**37**	**10.13 (3.38) A**	*****	**1.00 (0.22) A**	**0.35 (0.08) B**	**0.40 (0.09) B**	**N(log)**
Euprymna tasmanica	**36**	**6.15 (3.30) A**	*****	**0.91 (0.38) AB**	**0.16 (0.07) B**	**0.13 (0.06) B**	**N(log)**
Leptomithrax weitei	32	22.34 (9.10)	*	0.35 (0.29)	0.34(0.31)	0.32 (0.19)	G
Stelletta sp.	32	14.58 (6.53)	*	0.44 (0.21)	0.87 (0.41)	0.97 (0.61)	G
Chelidonichthys kumu	31	10.73 (3.54)	*	0.56 (0.24)	1.16 (0.32)	1.49 (0.57)	G
Lophiomus setigerus	31	5.65 (2.10)	*	3.03 (0.60)	1.36 (0.20)	2.17 (0.46)	G
Carangoides equula	29	95.48 (85.88)	*	0.89 (0.28)	1.31 (0.43)	0.80 (0.26)	N(log)
Neosebastes incisipinnis	**29**	*****	**0.35 (0.02) A**	**0.26 (0.02) B**	**0.30 (0.03) AB**	**0.22 (0.02) B**	**B**
Priacanthus macracanthus	29	23.47 (7.22)	*	0.71 (0.24)	0.73 (0.22)	0.80 (0.28)	G
Gonorynchus greyi	28	13.47 (4.02)	*	5.20 (5.25)	6.30 (7.18)	2.81 (3.55)	G
Gnathophis grahamii	**26**	*****	**0.41 (0.02) A**	**0.34 (0.05) A**	**0.13 (0.04) A**	**0.10 (0.03) B**	**B**
Dactyloptena papilio	25	7.60 (4.94)	*	0.46 (0.51)	0.54 (0.38)	0.76 (0.59)	G
Dentex spariformis	22	17.59 (16.23)	*	1.40 (0.65)	0.66 (0.51)	0.48 (0.38)	G

Species	**Occurrence (%) in 130 sub-samples (65 trawls x 2 nets)**	**Mean observed catch rate (g ha^{-1}) Standard net**	**Predicted probability of capture in Standard net**	**Change in catch rates based on generalised linear model predictions**			**Distribution type**
				TED only	**Square mesh codend BRD only**	**TED with Square mesh codend BRD together**	
Apogonops anomalus	**20**	**137.28 (88.54) A**	*****	**0.99 (0.18) A**	**0.52 (0.10) B**	**0.59 (0.11) B**	**N(log)**
Dipturus polyommata	19	*	0.17 (0.08)	0.14 (0.03)	0.24 (0.05)	0.22 (0.04)	B
Trachurus novaezelandiae	17	6.50 (4.20)	*	0.34 (0.15)	0.58 (0.19)	0.60 (0.22)	G
Glaucosoma scapulare	**15**	*****	**0.28 (0.08) A**	**0.12 (0.06) AB**	**0.13 (0.06) AB**	**0.06 (0.04) B**	**B**
Charybdis miles	14	5.72 (3.31)	*	1.72 (2.65)	0.84 (1.06)	2.39 (6.00)	G
Lagocephalus inermis	12	8.04 (4.69)	*	1.02 (0.12)	1.16 (0.15)	0.97 (0.12)	N(log)
Parapercis sp. _A_	**11**	**13.39 (7.93) A**	*****	**0.98 (0.15) A**	**0.68 (0.11) B**	**0.77 (0.12) AB**	**N(log)**
Saurida grandisquamis	**10**	**23.27 (14.37) AC**	*****	**0.86 (0.08) A**	**0.80 (0.08) B**	**1.08 (0.11) C**	**N(log)**
Macrorhamphosus molleri	10	21.75 (15.10)	*	0.98 (0.10)	0.84 (0.09)	0.83 (0.09)	N(log)
Asymbolus rubiginosus[1]	**9**	*****	**0.42 (0.003) A**	**0.42 (0.002) A**	**0.02 (0.00003) B**	**0.02 (0.0001) B**	**B**
Thamnaconus hypargyreus	9	*	0.13 (0.06)	0.06 (0.04)	0.06 (0.04)	0.06 (0.04)	B
Zeus faber	**8**	*****	**0.13 (0.02) A**	**0.02 (0.02) B**	**0.13 (0.03) AB**	**0.04 (0.05) AB**	**B**
Galeus boardmani	7	*	0.05 (0.0.03)	0.06 (0.04)	0.07 (0.03)	0.07 (0.02)	B
Nelusetta ayraudi	6	6.63 (6.63)	*	1.05 (0.09)	1.00 (0.08)	1.07 (0.09)	N(log)

[1] The significant difference and predicted probabilities of capture for this species are questionable, possibly due to a poor model-fit and should be interpreted with caution.

Table 9.4.3. Predicted mean length (mm) of bycatch species from the four codend types based on 130 sub-samples of bycatch (65 sites trawled x 2 nets). Generalised linear modelling was used to estimate the means using a normal distribution with identity link function. Significant differences between codends ($P < 0.05$) are bolded and identified by different alphabetic characters (A, B, C or D). Standard errors in parentheses.

		Predicted mean length			
Species	**Number of individuals measured**	**Standard net**	**TED only**	**Square mesh codend BRD only**	**Square mesh codend BRD and TED together**
Lepidotrigla argus	**1162**	**89.19 (2.22) A**	**95.11 (2.15) AB**	**101.07 (2.26) BC**	**102.07 (1.99) C**
Ratabulus diversidens	**778**	**196.39 (2.60) AC**	**190.53 (2.58) A**	**208.61 (2.79) B**	**199.10 (2.61) C**
Plesionika laurentae	733	15.45 (0.15)	15.15 (0.19)	15.62 (0.17)	15.34 (0.20)
Callionymus moretonensis	**711**	**105.59 (1.13) A**	**108.07 (1.25) A**	**116.64 (1.23) B**	**113.64 (1.20) B**
Peronella sp.	545	66.30 (1.68)	67.42 (1.36)	66.87 (1.53)	68.27 (1.65)
Charybdis bimaculata	474	36.90 (0.48)	36.82 (0.53)	37.78 (0.46)	37.32 (0.70)
Macrorhamphosus scolopax	456	88.50 (0.89)	90.43 (0.93)	91.20 (1.25)	90.54 (1.47)
***Aulotrachichthys* sp.**	**382**	**53.02 (0.61) A**	**53.41 (0.52) A**	**62.66 (2.41) B**	**65.12 (2.52) B**
***Calliactus* sp.**	**379**	**34.59 (1.52) A**	**31.58 (1.70) AB**	**28.62 (1.77) B**	**30.20 (1.59) AB**
Solenocera choprai	**377**	**22.79 (0.28) A**	**23.34 (0.43) AB**	**24.42 (0.37) B**	**24.44 (0.61) B**
Apogonops anomalus	**286**	**88.85 (1.25) A**	**96.66 (1.19) B**	**107.79 (2.66) C**	**102.84 (1.20) C**
Aulopus curtirostris	**262**	**84.58 (1.54) A**	**89.07 (1.45) A**	**100.31 (8.46) AB**	**102.59 (5.99) B**
***Stelletta* sp.**	**236**	**35.45 (1.01) A**	**29.74 (1.75) B**	**32.66 (1.43) AB**	**32.40 (2.04) AB**
Euprymna tasmanica	**227**	**17.13 (0.51) A**	**19.35 (0.46) B**	**18.66 (0.86) AB**	**19.21 (1.67) AB**
Kempina mikado	203	36.08 (0.90)	39.03 (1.18)	37.49 (0.95)	37.19 (1.06)
Dardanus arrosor	177	27.91 (2.89)	26.07 (3.06)	22.80 (2.74)	19.42 (2.99)
Parapercis* sp. *A	**174**	**85.14 (2.45) AC**	**85.03 (2.54) AC**	**120.28 (10.58) B**	**83.36 (12.80) C**
Saurida filamentosa	163	228.34 (11.92)	233.05 (8.81)	262.41 (11.39)	251.32 (23.66)
Trachurus novaezelandiae	154	154.48 (3.90)	153.10 (3.23)	157.20 (1.41)	154.85 (1.78)
Macrorhamphosus molleri	149	108.54 (1.85)	108.60 (2.65)	111.43 (1.75)	109.26 (2.23)
Dentex spariformis	**145**	**76.16 (2.84) A**	**85.10 (2.35) B**	**80.72 (3.38) AB**	**81.51 (2.91) AB**
Priacanthus macracanthus	129	171.66 (4.12)	171.61 (4.47)	167.67 (2.78)	167.67 (2.80)
Carangoides equula	**127**	**127.94 (2.59) A**	**128.61 (2.88) A**	**134.35 (3.38) AB**	**142.03 (4.87) B**
Dactyloptena papilio	89	103.35 (4.76)	104.30 (5.65)	102.14 (4.98)	108.35 (4.04)
Leptomithrax weitei	**77**	**105.32 (6.82) A**	**76.86 (10.49) B**	**83.38 (7.12) B**	**83.04 (3.94) B**
Gonorynchus greyi	**77**	**211.90 (24.60) AB**	**238.60 (10.80) A**	**281.50 (15.60) B**	**278.10 (17.40) B**

Species	Number of individuals measured	Predicted mean length			
		Standard net	TED only	Square mesh codend BRD only	Square mesh codend BRD and TED together
Neosebastes incisipinnis	71	101.99 (4.88)	89.69 (8.46)	104.96 (4.80)	105.63 (6.28)
Chelidonichthys kumu	70	187.81 (6.34)	197.92 (6.33)	186.11 (3.80)	189.16 (3.62)
Gnathophis grahamii	60	267.36 (9.60)	261.84 (14.38)	267.36 (9.60)	267.36 (9.60)
Lophiomus setigerus	**53**	**123.16 (9.70) AB**	**125.38 (6.34) AB**	**119.16 (5.20) A**	**140.81 (7.71) B**
Charybdis miles	50	51.14 (5.02)	62.66 (6.29)	54.27 (5.64)	69.99 (12.51)
Saurida grandisquamis	28	316.70 (34.20)	328.90 (81.40)	271.40 (119.10)	373.90 (28.60)
Lagocephalus inermis	27	130.60 (13.30)	115.50 (17.50)	105.00 (20.90)	181.70 (21.60)
Dipturus polyommata	23	257.30 (26.20)	*	142.30 (54.20)	381.30 (38.30)
Thamnaconus hypargyreus	23	133.54 (6.13)	136.04 (9.44)	126.88 (5.72)	122.88 (6.98)
Glaucosoma scapulare	22	175.55 (5.29)	186.98 (6.72)	201.98 (13.60)	175.55 (5.29)
Asymbolus rubiginosus	20	*	*	471.88 (36.81)	447.63 (7.24
Nelusetta ayraudi	12	439.20 (23.10)	405.80 (23.10)	439.20 (23.10)	439.20 (23.10)
Galeus boardmani	11	*	*	486.40 (24.10)	426.40 (11.00)
Zeus faber	10	*	*	*	*

*Too few individual measures for the model to predict means.

9.4.5 Bycatch species catch rates and power analysis

The power to detect change in bycatch species catch rates was examined for species whose catch rates conformed to gamma or binomial distributions. The results indicate, as predicted, the power to detect a change increases with a) decreasing variance for gamma-distributed species, and b) increasing probability of capture for binomial-distributed species (Figure 9.4.3).

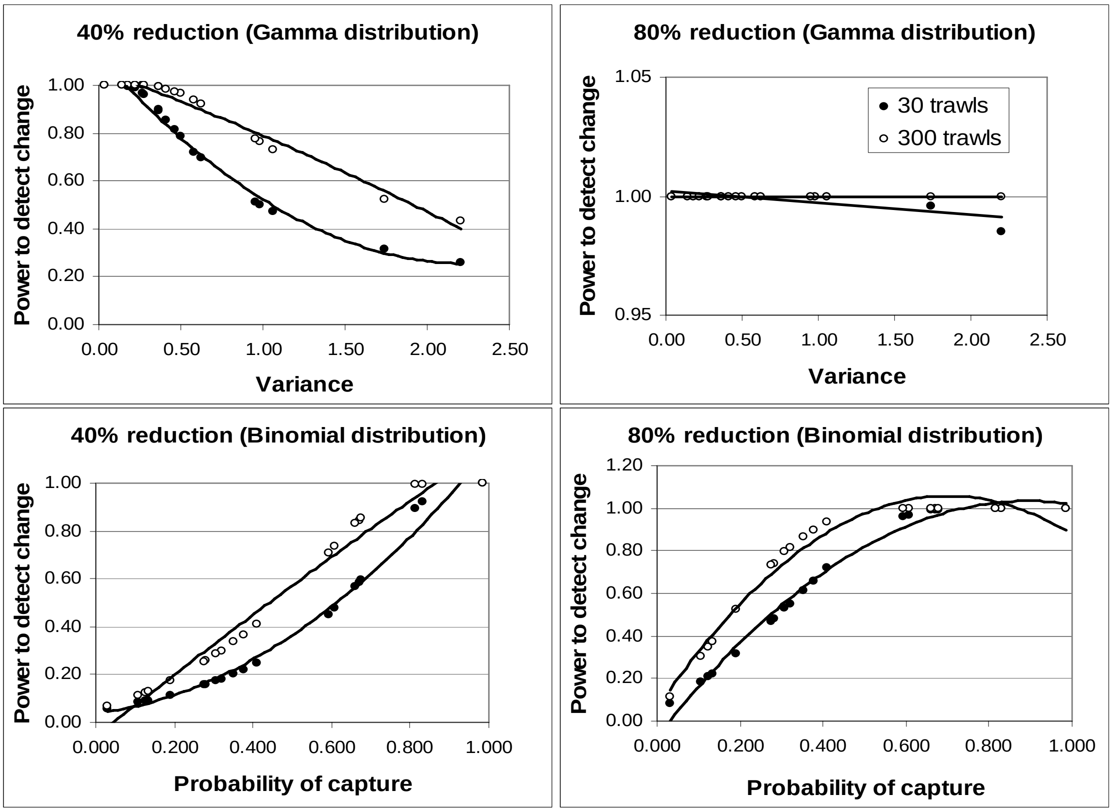


Figure 9.4.3. The power to detect change in bycatch species catch rates in the deepwater eastern king prawn fishery. Examples are provided for relatively small (40% reduction) and large changes (80% reduction) for species whose catch rates conform to either a gamma or binomial distribution. Two possible monitoring programs were considered, one based on 30 trawl samples and one based 300.

For gamma-distributed species, a monitoring program based on 300 trawl samples could detect a 40% change in catch rate with a power of 0.8 if the variance was about 1.0 or less. The variance would have to be significantly less, around 0.4–0.5, if a 30-trawl sample program was used. Both sampling programs could confidently detect an 80% change in catch rates, for the entire range of variances considered. For binomial-distributed species, a monitoring program based on 300 samples could detect a 40% decline in catch rate with a power of 0.8 if the probability of capture was about 0.7 or higher. If only 30 samples were used the probability of capture would have to be about 0.8 or above. If an 80% change in catch rate was to be used as the reference point, then the probability of capture would have to be about 0.5 or higher to detect the change at a power of 0.8 for a 300-sample program. If only 30 samples were used the probability of capture would have to be above about 0.75.

9.4.6 Effects on bycatch community structure

MDS was carried out using all 130 samples and the catch rates of 101 taxa that were present in 5% or more of the samples. The resulting stress value was 0.17 for a three-dimensional ordination. Analysis of similarities (ANOSIM procedure in PRIMER) revealed that bycatch assemblages differed significantly between depths (global *R* = 0.311, *P* < 0.001, Figure 9.4.4), with the largest *R*-statistic (i.e., greatest difference = 0.777) between the 110 m (shallowest) and the 150 m depth categories. Species that contributed 90% of the dissimilarity are listed in Table 9.4.4. It is noteworthy that almost half (42 out of 90) were completely absent from one or other depth categories. The shallowest (110 m) and deepest (170 m) categories had the second highest *R*-statistic of 0.728.

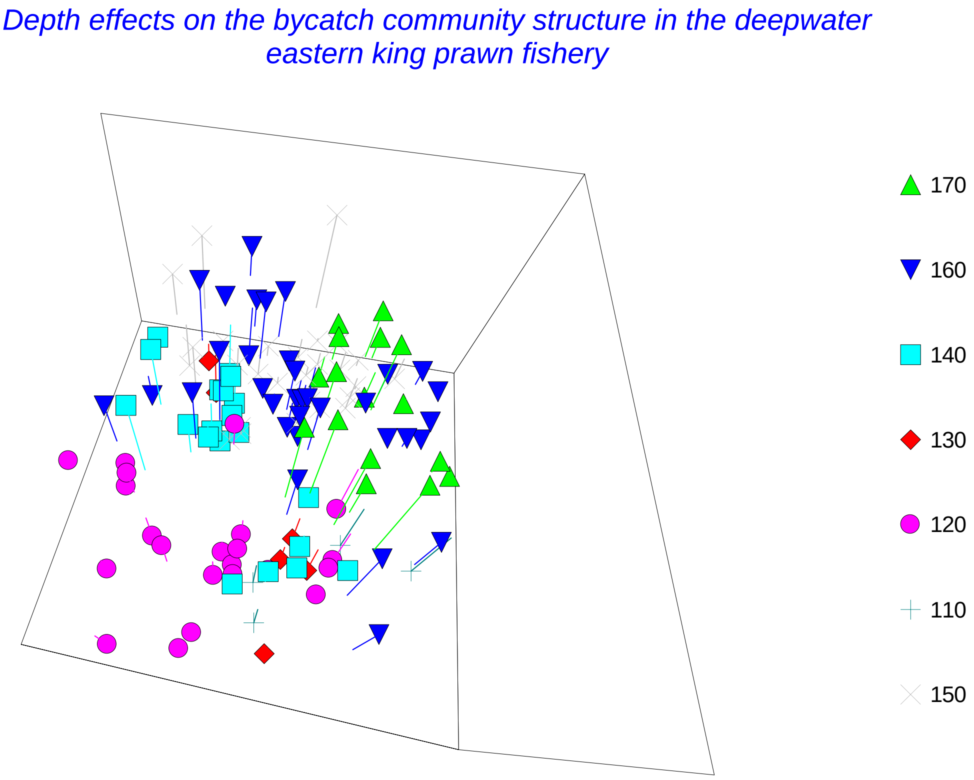


Figure 9.4.4. MDS of the deepwater eastern king prawn fishery bycatch showing groupings based on depth (global *R* = 0.311). Legend refers to depth (m).

Table 9.4.4. Species that contributed 90% of the dissimilarity between the shallowest (110 m) and 150 m depth groups in the deepwater (> 50 fm) eastern king prawn fishery bycatch. These two groups had the highest level dissimilarity (*R*-statistic = 0.777). Note the large number of species that were completely absent from one or other depth category.

Species/Taxa	**110 m depth group mean catch rate (g ha^{-1})**	**150 m depth group mean catch rate (g ha^{-1})**	**Average dissimilarity**	**Dissimilarity/Standard deviation**	**Contribution to dissimilarity %**	**% Cumulative dissimilarity**
Nemipterus theodorei	98.67	0	1.87	1.61	2.48	2.48
Saurida grandisquamis	214.78	7.01	1.75	0.98	2.32	4.8
Saurida filamentosa	294.99	40.14	1.74	1.07	2.31	7.11
Peronella sp.	6.42	60.24	1.67	1.59	2.21	9.32
Rubble	11.7	101.37	1.64	2.11	2.17	11.49
Prionocidaris sp.	75.49	0.68	1.62	1.94	2.14	13.64
Astropecten sp.	24.77	0.85	1.51	3.48	2	15.64
Callionymus moretonensis	66.18	3.57	1.38	1.85	1.83	17.47
Leptomithrax weitei	0.29	37.98	1.38	0.94	1.83	19.31
Dactyloptena papilio	54.99	0.86	1.38	1.33	1.83	21.13
Unidentified Sponge	38.03	3.67	1.37	1.5	1.81	22.95
Neosebastes incisipinnis	12.52	0	1.36	6.45	1.81	24.75
Nemipterus aurifilum	173.37	47.47	1.29	1.11	1.7	26.46
Parapercis sp. *A*	96.34	0	1.28	0.98	1.7	28.16
Portunus argentatus	44.87	0	1.21	1.28	1.61	29.77
Tetrosomus concatenatus	47.14	0	1.2	0.98	1.59	31.36
Kempina mikado	0	15.99	1.17	0.96	1.55	32.91
Ratabulus diversidens	69.2	121.42	1.12	1.51	1.48	34.39
Dardanus arrosor	0.65	9.12	1.09	1.58	1.44	35.83
Lepidotrigla argus	207.97	65.9	1.08	1.18	1.44	37.27
Charybdis bimaculata	46.41	2.39	1.07	1.53	1.42	38.69
Gnathophis grahamii	23.87	2.86	1.05	1.37	1.39	40.08
Stelletta sp.	0	14.74	1.04	1.11	1.38	41.46
Antennarius striatus	7.83	0.41	0.92	1.62	1.22	42.68
Sympagurus sp.	0	1.58	0.9	2.26	1.19	43.87
Carangoides equula	22.79	0	0.9	0.99	1.19	45.06
Gonorynchus greyi	0	22.08	0.87	0.72	1.15	46.21
Macrorhamphosus scolopax	0	4.64	0.85	1.16	1.12	47.34
Uranoscopus terraereginae	20.51	2.86	0.84	0.96	1.11	48.45

Species/Taxa	110 m depth group mean catch rate (g ha^{-1})	150 m depth group mean catch rate (g ha^{-1})	Average dissimilarity	Dissimilarity/Standard deviation	Contribution to dissimilarity %	% Cumulative dissimilarity
Charybdis miles	18.91	0.25	0.83	0.98	1.1	49.54
Sepia opipara	10.82	3.67	0.8	1.08	1.06	50.6
Aptychotrema rostrata	53.85	0	0.79	0.57	1.05	51.65
Glaucosoma scapulare	5.19	19.95	0.78	0.78	1.03	52.68
Lophiomus setigerus	6.35	7.5	0.76	0.83	1.01	53.69
Grammatobothus polyophthalm	7.44	0	0.75	0.98	1	54.69
Solenocera bifurcata	3.13	0.23	0.72	1.89	0.96	55.65
Antigonia rhomboidea	2.57	0.37	0.71	1.9	0.94	56.59
Sirembo metachroma	6.38	2.71	0.71	1.03	0.94	57.53
Plesionika laurentae	2.28	2.3	0.69	1.05	0.92	58.45
Quollastria gonypetes	0.45	2.83	0.67	0.9	0.88	59.33
Photololigo sp.	3.48	1.85	0.66	1.06	0.88	60.21
Psettina gigantea	3.2	0.31	0.65	1.4	0.86	61.07
Sepioloidea lineolata	6.53	0	0.65	0.97	0.86	61.93
Aulopus curtirostris	1.48	0.78	0.64	1.7	0.85	62.77
Solenocera choprai	1.99	3.59	0.63	1.11	0.84	63.61
Amusium balloti	3.02	0	0.6	0.97	0.8	64.41
Chelidonichthys kumu	8.01	5.49	0.6	0.69	0.8	65.21
Raja polyommatta	0	12.54	0.6	0.6	0.8	66.01
Euprymna tasmanica	0.15	4.77	0.6	0.74	0.79	66.8
Lepidotrigla grandis	3.67	0.43	0.6	1	0.79	67.59
Synodus macrops	3.96	0	0.59	0.98	0.78	68.37
Halieutea stellata	1.33	1.13	0.58	1.09	0.77	69.14
Aulotrachichthys sp.	0	3.25	0.57	0.8	0.75	69.9
Glossanodon australis	0	2.28	0.56	0.85	0.75	70.64
Priacanthus macracanthus	7.37	3.45	0.56	0.6	0.75	71.39
Asymbolus rubiginosus	0	16.98	0.56	0.57	0.74	72.13
Sphenopus marsupialus	1.94	0	0.54	0.98	0.71	72.84
Dendrodoris tuberculosa	5.69	2.39	0.53	0.6	0.7	73.54
Calliactus sp.	5.11	6.11	0.49	1.27	0.66	74.2
Lupocyclus philippinensis	0.66	0.02	0.49	1.57	0.65	74.85
Xanthid sp.	0	0.27	0.49	1.46	0.64	75.49
Trachinocephalus myops	12.93	0	0.48	0.57	0.63	76.13

Species/Taxa	**110 m depth group mean catch rate (g ha^{-1})**	**150 m depth group mean catch rate (g ha^{-1})**	**Average dissimilarity**	**Dissimilarity/Standard deviation**	**Contribution to dissimilarity %**	**% Cumulative dissimilarity**
Sea Urchin 3	12.92	0	0.48	0.57	0.63	76.76
Ibacus chacei	0.33	0.82	0.47	1.12	0.63	77.39
Neosebastes cf entaxis	1.69	0	0.47	0.95	0.62	78.02
Sepia whitleyana	6.17	0	0.46	0.57	0.61	78.63
Plagiopsetta glossa	0	1.21	0.46	0.76	0.61	79.24
Pristigenys niphonia	1.1	0	0.46	0.96	0.61	79.85
Anoplocapros inermis	13.08	0	0.46	0.57	0.61	80.45
Sepia limata	0.32	0.68	0.46	1.19	0.61	81.06
Champsodon nudivittis	1.05	0.16	0.45	0.98	0.59	81.65
Chelidoperca sp.	1.14	0	0.42	0.98	0.56	82.21
Pseudorhombus tenuirastrum	4.3	0	0.42	0.57	0.56	82.77
Microcanthus strigatus	0	5.46	0.4	0.49	0.53	83.3
Zeus faber	0	9.37	0.38	0.45	0.5	83.8
Trachurus novaezelandiae	3.19	0.18	0.36	0.6	0.48	84.28
Sea star 101	0.56	0	0.36	0.98	0.48	84.76
Ophidion muraenolepis	0	1.56	0.36	0.52	0.47	85.23
Pontocaris orientalis	0.52	0.01	0.36	1	0.47	85.7
Pseudorhombus dupliciocella	3.88	0	0.35	0.57	0.47	86.17
Chloeia sp.	0.49	0.29	0.34	0.71	0.45	86.62
Penaeus plebejus	1.65	0	0.33	0.57	0.44	87.06
Harpiosquilla sinensis	2.98	0	0.33	0.57	0.43	87.49
Fistularia petimba	0	2.69	0.32	0.45	0.43	87.92
Unidentified Crinoid	1.8	0.05	0.32	0.65	0.43	88.35
Xenophora peroniana	0	2.49	0.32	0.5	0.42	88.77
Sea Urchin 6	1.32	0	0.31	0.57	0.42	89.19
Samaris macrolepis	1.32	0	0.31	0.57	0.42	89.6
Sepia plangon	1.88	0	0.3	0.57	0.39	90
Callionymus margaretae	0.97	0	0.29	0.57	0.39	90.38

Bycatch assemblages were also strongly affected by latitude (global *R* = 0.429, *P* < 0.001). The largest difference was between the 26.5 ^{o}S group and the 27.5 ^{o}S group (*R*-statistic = 0.711, Figure 9.4.5).

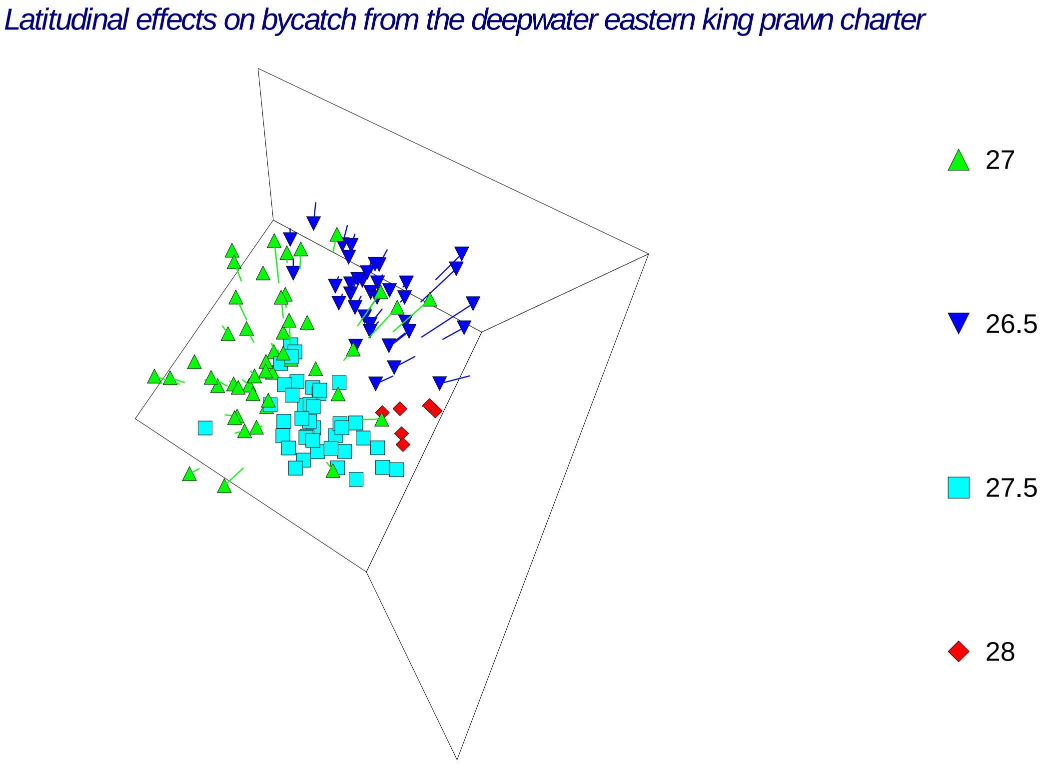


Figure 9.4.5. MDS of bycatch from the deepwater eastern king prawn fishery showing strong evidence (global *R* = 0.429) of latitudinal grouping. Legend in latitude (degrees south).

Because latitude had such a marked influence on the bycatch, the effects of the codend types were examined using a two-way crossed analysis of similarities (ANOSIM). While the strong latitudinal effect was confirmed, the global *R* value for codend type was 0.075 (*P* = 0.06), suggesting that the codend type had no significant effect on the bycatch assemblages.

9.5 DISCUSSION

The main finding from the charter was that bycatch in the deepwater eastern king prawn fishery can be significantly reduced, by 29% ($\boldsymbol{\beta}_3$ estimate of 0.71, Table 9.4.1) with no loss of the targeted eastern king prawns. Prawn catch rates were low throughout the charter. This was probably because the location of the trawls was determined using previous effort data and included locations with low catch rates. Normally, if areas with high catch rates were found then fishers would remain in those areas. However, for the purposes of our study, it was important to sample sites throughout the entire area and not just those areas with higher catch rates.

As with the bycatch rates, the prawn catch rates from the codend with the TED only were comparable to those from the standard net. A lack of bottom debris or large animals in the deepwater fishery indicated that the TED's escape hole cover, or flap, remained closed throughout the trawl, preventing prawns from escaping. It should be noted that, with such a reduction in bycatch (i.e., 29% reduction), the catch rate of prawns might increase. Because the net caught less bycatch it probably experienced less drag and therefore maintained a higher spread ratio, which allowed it to sweep over a larger area. This would likely have resulted in higher catch rates. Considering that trawl duration in the deepwater fishery is usually three to six hours, this could result in a significant increase in the area trawled and subsequently greater catches.

There was no difference in the size of the prawns caught from the four codend types (Figure 9.4.1). Therefore, it is possible that even larger square mesh could have been used resulting in even greater bycatch reduction. Further testing of square mesh codends could include experiments to determine the optimum mesh size where bycatch exclusion rates are maximised without reducing prawn catch rates.

The study also showed that the TED significantly reduced the catch rate of Balmain bugs, *Ibacus chacei* (Figure 9.4.2), which is consistent with the reduced catch rate of Moreton Bay bugs *Thenus orientalis* attributed to the TED during the scallop fishery charter (Chapter 7). These species are high-value byproduct in the prawn and scallop fisheries and there is a strong need to understand how management changes (i.e., the introduction of TEDs) in recent years have affected their catch rates.

The results are very promising because they demonstrate that bycatch can be significantly reduced without any significant effect on the prawn catch rates or sizes. There were two factors that contributed to these favourable results. Firstly, the location of the square mesh codend within the net allowed a greater number of animals to escape the trawl. Other BRDs, including the bigeye, fisheye or radial escape section, are located up to 100 meshes forward of the drawstring which is where the catch accumulates. As such, small fish must swim this distance, at a speed greater than the net is travelling, to escape. This is a difficult task because the fish are likely to tire from trying to evade capture before reaching the codend and because they generally lack swimming speed and stamina. In contrast to other BRDs, the catch accumulates in the square mesh codend BRD allowing small fish and other animals to escape after swimming a much smaller distance. Further, animals such as small crabs have a much better chance of escaping from a square mesh codend, and probably simply fall through the meshes. Secondly, the large size of the targeted adult eastern king prawns (i.e., *P. plebejus* is the largest of Australia’s endemic prawn species), facilitates the use of square mesh codends, which allow the smaller fish and other animals to escape. If smaller mesh is used, which is one method of reducing prawn loss, it is likely that the bycatch catch rates would increase. Generally, square mesh codend BRDs are effective in fisheries where the target species are larger than the majority of the bycatch species. Square mesh codends may not be suitable for some sectors of the Queensland East Coast Trawl Fishery.

9.5.1 Effects on bycatch species and community structure

Of those species that could have robust analyses undertaken on them (Table 9.4.2.), 38% experienced a significant reduction in catch rate due to the TED, square mesh codend BRD or both. Several species experienced reductions between 70 and 87% and most reductions were attributed to the square mesh codend, rather than the TED. Although the overall 29% reduction in bycatch catch rate is very promising, it did not appear large enough to alter the general character of the bycatch. Much of the variation in bycatch community structure is explained by depth (Figure 9.4.4) and latitude (Figure 9.4.5), and the codend types only had a marginal impact on altering the bycatch community structure.

9.5.2 Extrapolating the charter results to the fishery

The total weight of bycatch produced annually throughout the entire Queensland East Coast Trawl Fishery is unknown, but likely to exceed 25,000 tonnes. Given that the deepwater eastern king prawn fishery produces about 700 tonnes of large oceanic king prawns annually, research data obtained from measuring bycatch rates from the commercial vessels during the opportunistic sampling (see Chapter 10) suggests that it would produce about 1400 tonnes of bycatch annually. If fishers were to adopt the square mesh codend in conjunction with the TED as their BRD, then the total expected reduction in bycatch from the deepwater king prawn fishery would equate to about 406 tonnes annually. [Note that this would be a significant improvement given that the opportunistic sampling suggests that the devices currently being used by fishers in the deepwater eastern king prawn fishery are having no significant effect on bycatch rates (Table 10.4.5)].

9.5.3 Power analysis and monitoring

The power analysis results are similar to those obtained from the north Queensland tiger/endeavour prawn charter (Chapter 6, section 6.4). The only difference is that a broader range of variances were obtained in the deepwater bycatch species analyses, which facilitated a broader range of power analyses to be examined. All power analyses undertaken thus far suggest similar results, that is, that the variance in mean catch rate for gamma-distributed species needs to be less than about 0.4–0.5 to confidently detect a 40% change in catch rate, based on a 30-trawl sample program. Obviously, more species could be monitored at this 40% reference point level if the program was increased to 300 samples. Before implementing bycatch monitoring programs for any of the major Queensland trawl fishery sectors it would be prudent to discuss possible action plans, should declines in one or more species be detected.

9.6 REFERENCES

Bray, J.R., Curtis, J.T., 1957. An ordination of the upland forest communities of Southern Wisconsin. Ecol. Monogr. 27, 325-349.

Clarke, K.R., Warrick, R.M., 1994. Change in marine communities: an approach to statistical analysis and interpretation. Plymouth Marine Laboratories, Plymouth.

GenStat, 7th ed., 2005. Lawes Agricultural Trust.

Montgomery, D.C., 1997. Design and Analysis of Experiments, 4th ed., John Wiley and Sons.

Stobutzki, I., Miller, M., Jones, P., Salini, J., 2001. Bycatch diversity and variation in a tropical Australian penaeid fishery; the implications for monitoring. Fish. Res. 53, 283-301.

10 Quantifying the performance of bycatch reduction devices (BRDs) on board vessels during their normal fishing activities – an assessment based on “opportunistic” measures of bycatch rates

A. J. Courtney, M. J. Campbell, M. L. Tonks, S. W. Gaddes and K. E. Chilcott

10.1 ABSTRACT

This chapter examined the effects of the TEDs and BRDs that fishers were using and was based on “opportunistic” measures of bycatch, prawn and scallop catches obtained by project staff on board vessels during their normal commercial fishing operations (as opposed to previous chapters which evaluated BRD effects from dedicated, controlled, experimental research charters). The conclusions should be interpreted with caution because of the lack of experimental control during such opportunistic sampling. Bycatch rates varied with fishing sector; the scallop fishery had the highest bycatch rate (9.39 S.E. 1.02 kg ha^{-1}) while the deepwater eastern king prawn sector had the lowest (1.30 S.E. 0.19 kg ha^{-1}). When the north Queensland tiger/endeavour prawn and eastern king prawn sectors were pooled, generalised linear modelling indicated that there was no significant reduction in the total mean bycatch rate (i.e., including large fauna or “monsters”) due to TEDs and BRDs. When large fauna were omitted from the analysis, mean bycatch rates (i.e., excluding monsters) declined significantly by 25% when the TEDs and BRDs were used together. No significant effects on marketable prawn catch rates were detected in this analysis. In the shallow water and deepwater eastern king prawn sectors, no significant reduction in total mean bycatch rate (i.e., including monsters) or mean bycatch rate (i.e., excluding monsters) were detected, due to TEDs or BRDs, nor was there any effect on mean marketable prawn catch rate. In the north Queensland tiger/endeavour prawn fishery, a 9% reduction in the catch rate of a) total mean bycatch rate (i.e., including monsters), b) bycatch rate (i.e., excluding monsters) and c) marketable prawns was detected due to the combined effects of TEDs and BRDs. These reductions were statistically significant. In the scallop fishery, a significant reduction in total mean bycatch rate (i.e., includes monsters) of 68% was detected, mainly due to TEDs excluding large bycatch species, predominantly sponges. A significant reduction (11%) in the mean scallop catch rate was also detected, mainly due to the BRDs. In general, the reductions in bycatch rates were low compared to those achieved during the research charters. The results can be used to evaluate bycatch reduction management measures and to plan and prioritise future initiatives.

10.2 INTRODUCTION

The Queensland *Fisheries (East Coast Trawl) Management Plan 1999* provides fishers with a choice of seven BRDs that they can choose from and install in their nets: 1) radial escape section, 2) fisheye, 3) square mesh panel, 4) square mesh codend, 5) bigeye, 6) Popeye fishbox, and 7) V-cut. The last two devices have only recently been approved and it is likely that further devices will be developed and included in the future. Otter trawl fishers are required, by law, to install at least one of these devices with a TED in each net, with the exception of their try-gear net. The previous chapters (Chapters 5 through to 9) quantified the effects of some of these devices with and without TEDs, under controlled experimental conditions in the major Queensland trawl sectors.

While the research charters provided valuable quantitative information on the effectiveness of the BRDs and TEDs, they do not necessarily provide insight on the performance of devices being used by the fleet. Although the charter designs went to considerable length to reflect commercial fishing conditions, (i.e., they deployed commercial vessels, commercial skippers and crews, used commercial trawl gear, were undertaken in the major trawl sectors in grounds that experienced medium to high levels of trawl fishing effort) it would be incorrect to assume that the reductions that were achieved reflected those of the commercial fleet. It was never intended that the charters' results would be representative of the bycatch reductions that were occurring in the fishery, but rather to show the expected or potential reductions in bycatch that could be achieved from certain devices in select sectors. In order to comment on the effectiveness of the devices that are being used by the fleet it was therefore necessary to undertake a second opportunistic sampling program that was focused specifically on quantifying the effects of BRDs and TEDs that the fleet were using. Project staff refer to these as "opportunistic" commercial vessel sampling data, while those of the research charters are referred to as "charter" data. To this end, this chapter quantifies the effects of the BRDs and TEDs being used by the fleet in the major Queensland trawl sectors based on the opportunistic sampling of vessels.

It should be noted that evaluating the performance of BRDs and TEDs at sea on commercial vessels while they are undertaking their normal fishing activities is challenging and in general results in limited robust quantitative data and conclusions. Researchers have very limited control over the experimental design and quality of data while sampling opportunistically. This lack of control greatly reduces our ability to quantitatively assess the bycatch reduction devices. Examples of the lack of control include:

a) inability to ensure all nets being towed on any particular vessel have no significant differences in their catch rates, irrespective of whether they have a BRD or TED installed;
b) side-of-boat or net position effects. For various reasons, the position of the net (i.e., inner port, outer port, inner starboard, outer starboard, stern) may result in it catching more, or less than the other nets, thus affecting interpretation of results;
c) reluctance of the skipper or crew to swap codend treatment types from one side of the vessel to another or from one net position to another, according to a robust statistical design;
d) a reluctance of the skipper or crew to remove the TED (because it may take too long to reinstall) in order for the net to be compared against another identical net with no TED installed;
e) reluctance of the skipper or crew to trawl along a straight line, which is required to ensure the areas swept by all nets being examined are equal; and
f) an inability to obtain a statistically adequate number of measurements.

All of these limitations were overcome by chartering vessels. Although the opportunistic data are not as statistically robust as the research charter data, they nevertheless provide some insight into the performance of the BRDs and TEDs that fishers are using. This chapter therefore presents data, results and conclusions on the effects of the BRDs and TEDs that trawl operators in the major Queensland trawl fishery sectors are using. Specifically, the effects on the catch rates of bycatch, prawns and scallops were quantified. The data, results and conclusions should be interpreted with caution due to the lack of experimental control.

10.3 MATERIALS AND METHODS

10.3.1 Obtaining measures of target species and bycatch catch rates

Fishers were usually approached over the phone and asked if they would allow a researcher on board their vessel for a few nights during normal fishing activities to measure and record the catch rates of bycatch and target species for the purposes of assessing the effectiveness of the TEDs and BRDs they were using.

Fishers who were trawling in the main trawl fishing sectors were approached. The project assumed that a) where there was more trawl fishing effort there was likely to be more bycatch produced, and b) because we were sampling commercial vessels from the main trawling sectors and areas, that the prawn, scallop and bycatch catch rates were representative of the fleet. Information recorded for each net at each trawl location while at sea included:

a) trawl location determined by the vessel's GPS, including the latitude and longitude where the trawl commenced and finished;

b) mean speed of the trawl, trawl duration and mean depth;

c) head rope length, and other details of the net, including its position (i.e., port, starboard, middle, outer port, etc.);

d) presence or absence of BRD and/or TED;

e) BRD type;

f) weight of the retained target species catch including eastern king prawns, *Penaeus plebejus,* brown tiger prawns *Penaeus esculentus*, blue-legged king prawns, *Penaeus latisulcatus*, endeavour prawns *Metapenaeus endeavouri* and *Metapenaeus ensis*, and saucer scallops *Amusium japonicum ballotti*;

g) large species weighing more than about 5 kg, endangered species or species that were considered to be of high conservation status were identified, weighed to the nearest 1.0 kg, recorded and released before the remaining bycatch was processed. Collectively these species include turtles, sea snakes, large sponges, large sharks and rays, and are referred to as monsters; and

h) the remaining bycatch weight was recorded to the nearest 1.0 kg. A sub-sample of the bycatch was retained and processed in the laboratory to species level. Details of all bycatch species recorded from each sector from the research charters and the opportunistic sampling are provided in Appendices 1, 2, 4 and 5.

The total weight of bycatch from any given net and trawl was estimated as the sum of the monster weight and the remaining bycatch weight. It was necessary to record the bycatch weight in this way because an infrequent catch of a single large animal, such as a shark, ray, turtle or sponge can skew the data and affect the overall predicted means and therefore the conclusions about the effectiveness of the TEDs and BRDs. The marketable catch of prawns and scallops from each net was determined by the crew after each trawl, and then weighed by the researcher. It is important to note that the marketable targeted catch was not defined by researchers. In this way, the weight of the targeted catches more closely reflects those of the industry.

The configuration of the nets towed by vessels in the eastern king prawn and scallop fisheries was typically triple gear (three nets towed from the port, starboard and stern of the vessel), while vessels in the north Queensland tiger/endeavour prawn fishery typically towed quad gear (four nets, with two nets on either side of the vessel) (O'Neill et al., 2005). To assess the effect of the devices the crew were asked to remove the TED and BRD from one net, either port or starboard, to facilitate a paired comparison with a standard net during each trawl (i.e., catch rates from a standard net compared to a net with a TED or BRD, or both). However, fishers were often reluctant to remove one or both devices from a net. When this occurred it prevented any simultaneous paired comparison of treatments from being obtained and compromised the statistical integrity of the sampling program. Measurements from the stern net were not considered because it fishes differently from the port and starboard nets and because no simultaneous paired comparison was possible.

10.3.2 Calculating catch rates

All catch rates were converted to weight (kg or g) per swept area trawled (hectares, ha). The area swept *S* by net *n* during trawl *t* was estimated thus:

$$S_{tn} = \frac{H \times F \times D}{10{,}000}$$

where *H* was the headline length of the net, *F* was the net spread factor from Sterling (2005) and *D* was the distance trawled. Division by 10,000 converts the area from square metres to hectares.

10.3.3 Statistical design and analyses

Generalised linear modelling (GLM) using GenStat (2005) statistical software was used to examine the variation in catch rates of bycatch and target species (i.e., prawns or scallops). Each trawl site location was treated in the model as a blocking term. The model was an accumulated analysis of variance with the following distributions and link functions: a) normal distribution with identity link, and b) gamma distribution with logarithm link function. Catch rates for target species, bycatch (discarded bycatch minus monster weight) and total bycatch (bycatch weight plus monster weight) were the response variables in all models. When a normal distribution was used, the response variable was either log-transformed [$x = ln\ (y)$] or square-root transformed [$x = \sqrt{}\ (y)$], depending on the homoscedasticity of the residual output. When a gamma distribution and logarithm link function were used the raw, non-transformed response variable data were used. The best model goodness-of-fit was obtained by examining plots of the standardised residuals and if they were found to be non-normally distributed then the model distribution type or transformation would be changed until normality was attained. Treatment factors and interaction terms were added in a forward step-wise procedure and then dropped from the model if they were found to have no significant effect. The models took the following general form:

$$U = \beta_o + \beta_1(\text{Trawl site}_{1-\text{n}}) + \beta_2(\text{Codend type}_{1-4}) + \varepsilon$$

where *U* was the predicted mean catch rate of bycatch weight, prawn weight or saucer scallop weight, *n* was the number of sites trawled, $\boldsymbol{\beta_o}$ was an estimated scalar parameter, $\boldsymbol{\beta}_1$ and $\boldsymbol{\beta}_2$ were vector parameters that were estimated and ε was the error term. Only estimates of $\boldsymbol{\beta}_2$ are presented as this parameter quantifies the effects of the different codend types. This model differs from the models used for the research charters in that the research charters could control the net position and side-of-boat that the different codend treatments were being tested in. During the opportunistic sampling however, the researchers had no control over these factors, and for these reasons, the model is simpler and does not include terms for net position or side-of-boat effects. For purposes of interpretation and consistency with the statistical methods used in previous chapters, the $\boldsymbol{\beta}_2$ parameter estimates have been proportionally scaled so that they could be compared against a standard codend parameter value of 1.0.

Because there are several different types of BRDs and TEDs that fishers can use, the number of observations that could be obtained for a specific BRD, or a specific BRD and TED combination, was low. Therefore sufficient observations required for a robust analysis of each specific device or combination of BRD and TED were not possible. Codend treatment types were therefore pooled and categorised to four levels:

1) Standard net only (with no BRD or TED)
2) BRD only (this included all recognised BRDs listed in the Management Plan)
3) TED only, and
4) BRD and TED together.

Results were presented as the observed mean catch rate (kg ha^{-1}) from the standard net and the effect of the codend type (i.e., BRD, TED, or BRD and TED together) was displayed as a proportional change in catch rate based on the parameter estimates generated by the model.

10.4 RESULTS

Between April 2000 and April 2002, catch rate information was recorded from 434 individual commercial net trawls (Table 10.4.1). The spatial distribution of the trawl locations is provided in Figure 10.4.1.

Table 10.4.1. Number of individual net trawls for each codend type in each sector. There were so many different TEDs, BRDs, and combinations of the two, used by fishers that four broad categories were identified to represent all possibilities. These were 1) Standard codend (i.e. no BRD or TED), 2) TED only, 3) BRD only, and 4) TED and BRD together.

Codend type	**Tiger/Endeavour prawn**	**Shallow water EKP**	**Deepwater EKP**	**Scallop**
Standard codend	64	27	40	43
BRD only	0	14	36	10
TED only	0	12	3	45
BRD and TED together	64	35	0	41
Total	**128**	**88**	**79**	**139**

Bycatch rates were dependent on sector, with the scallop fishery producing the highest bycatch rates (9.39 S.E. 1.02 kg ha^{-1}), and the deepwater eastern king prawn fishery producing the lowest (1.30 S.E. 0.19 kg ha^{-1}). The mean observed catch rate of prawns from all sectors was 0.93 (S.E. 0.06) kg ha^{-1}, while the mean observed catch rate of scallops was 3.00 (S.E. 0.20) kg ha^{-1}.

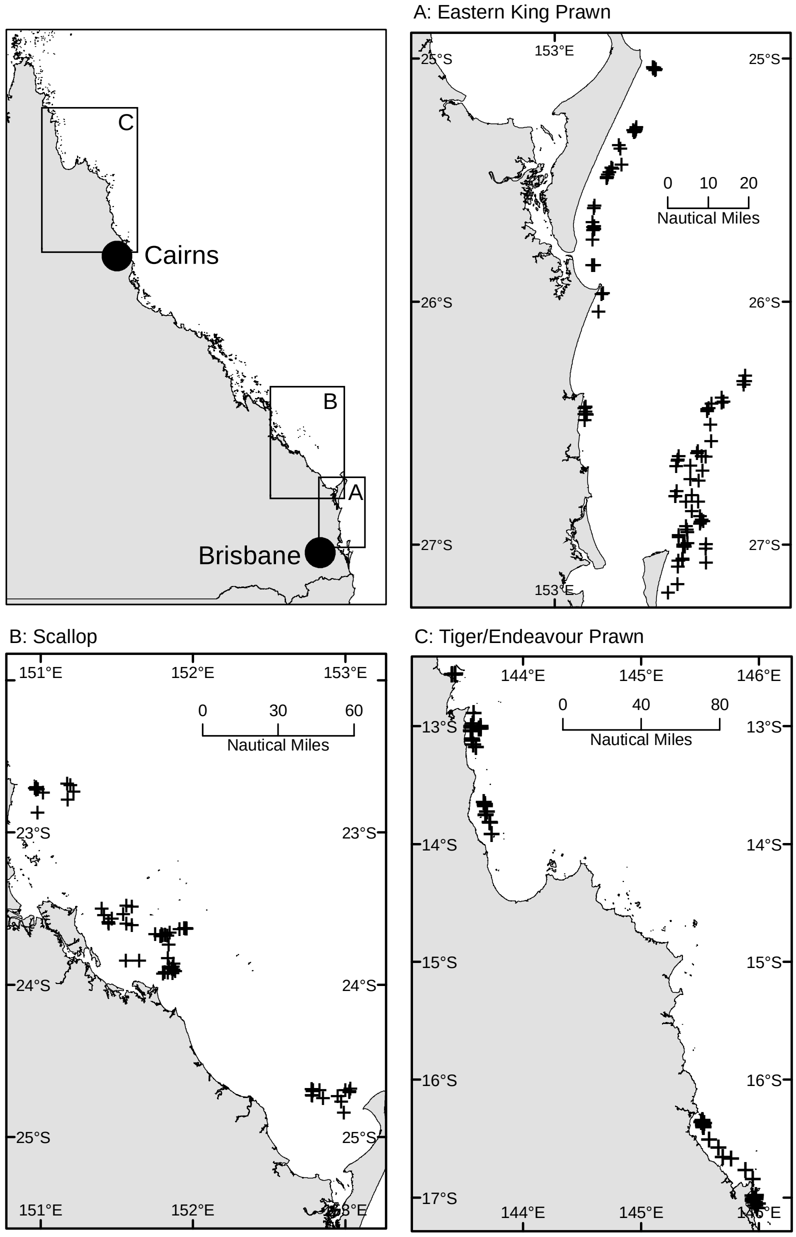


Figure 10.4.1. Locations where measures of target species and bycatch catch rates were obtained during the opportunistic sampling program for the (A) eastern king prawn fishery, (B) the scallop fishery and (C) the tiger/endeavour prawn fishery. These sectors account for about 80% of the trawl fishing effort and catch in Queensland.

10.4.1 Types of bycatch reduction devices that were evaluated

Catch rates of bycatch and target species were measured from a range of codend types. Queensland trawl fishers are required to have a TED and one of seven recognised BRDs installed in their nets. Table 10.4.2 provides a numerical breakdown of the codend types sampled in each sector during the opportunistic sampling program.

Table 10.4.2. Number of measurements obtained from individual net trawls in each sector for each different codend type obtained during the opportunistic sampling program. The numbers include observations where the BRDs were inserted with, and without TEDs.

Codend type	**Tiger/endeavour prawn**	**Shallow water eastern king prawn**	**Deepwater eastern king prawn**	**Scallop**
Bigeye	0	21	15	37
Fisheye	0	15	0	15
Square mesh panel	8	6	24	0
Radial escape section	16	0	0	0
Square mesh codend	0	0	0	0
V-cut	40	7	0	0
None (standard net)	64	27	40	41
TED only	0	12	0	46

10.4.2 Effects of BRDs on prawn catch rates

When all of the prawn sectors (i.e., shallow water eastern king prawn, deepwater eastern king prawn and north Queensland tiger/endeavour prawn) were grouped and generalised linear modelling undertaken on 295 observations, the model parameter estimates indicated no statistically significant reduction in total mean bycatch (i.e., including monsters) rate due to TEDs and BRDs (Table 10.4.3). When large bycatch were omitted from the analyses (i.e., bycatch excluding monsters), a significant reduction of 25% was detected when both the TED and BRD were installed compared to a standard net (β_2 parameter estimate of 0.75, Table 10.4.3). The analyses suggest that the inclusion of infrequently caught large individuals (such as large sharks, rays and sponges) complicates the analysis and may sometimes mask the detection of reductions in bycatch rate. The analyses indicated that TEDs alone, and BRDs alone, had no significant effect on bycatch rates (excluding monsters), but when used together significant reductions were detected. None of the codend types had a significant effect on mean prawn catch rate compared to the standard net.

Table 10.4.3. Mean catch rates of total bycatch, bycatch and marketable prawns from all prawn sectors combined based on 295 individual net tows obtained by opportunistically sampling on board fishing vessels in the eastern king prawn and north Queensland tiger/endeavour prawn sectors. Generalised linear modelling was used to quantify the effects of codend type. Significant differences between treatments (*P* < 0.05) are bolded and identified by different alphabetic characters (A, B, C or D). The parameter estimates have been proportionally scaled so they can be compared to a standard net parameter value of 1. Standard errors in parentheses.

Response variable	**Mean observed catch rate in kg ha^{-1} from standard net**	**Generalised linear model parameter estimates (Proportionally scaled to a standard net parameter value of 1)**			**Distribution type**
		TED only	**BRD only**	**BRD and TED together**	
Total bycatch (includes monsters)	**3.79 (0.33) AB**	**1.40 (0.30) A**	**0.98 (0.09) AB**	**0.92 (0.06) B**	**Gamma**
Bycatch (excludes monsters)	**3.73 (0.32) A**	**1.21 (0.12) A**	**0.84 (0.04) A**	**0.75 (0.02) B**	**Gamma**
Marketable Prawns	0.93 (0.06) A	0.93 (0.01) A	1.00 (0.01) A	0.93 (0.01) A	Normal (square-root transformed)

10.4.3 Shallow water eastern king prawn fishery

Analysis of the 88 individual net catch rate data indicated that the BRDs used in the shallow water eastern king prawn fishery had no significant effect on either total mean bycatch (i.e., including monsters) rate or mean bycatch (i.e., excluding monsters) rate (Table 10.4.4). Mean prawn catch rate was not significantly affected by the BRDs or TEDs used by fishers, nor was it affected when both devices were used together ($\boldsymbol{\beta}_2$ parameter estimate of 0.90, Table 10.4.4).

Table 10.4.4. Mean catch rates of total bycatch, bycatch and target prawn species in the shallow water (< 50 fm) eastern king prawn *Penaeus plebejus* fishery based on 88 individual net tows obtained by opportunistically sampling on board fishing vessels. Generalised linear modelling was used to quantify the effects of codend type. Significant differences between treatments (*P* < 0.05) are bolded and identified by different alphabetic characters (A, B, C or D). The parameter estimates have been proportionally scaled so they can be compared to a standard net parameter value of 1. Standard errors in parentheses.

Response variable	**Mean observed catch rate in kg ha^{-1} standard net**	**Generalised linear model parameter estimates (Proportionally scaled to a standard net parameter value of 1)**			**Distribution type**
		TED only	**BRD only**	**BRD and TED together**	
Total bycatch (includes monsters)	5.48 (1.30) A	1.66 (0.55) A	1.04 (0.28) A	0.91 (0.15) A	Normal (log transformed)
Bycatch (excludes monsters)	5.21 (1.25) A	1.43 (0.06) A	1.10 (0.06) A	0.88 (0.06) A	Normal (square-root transformed)
Marketable Prawns	1.20 (0.13) A	0.78 (0.15) A	1.04 (0.17) A	0.90 (0.09) A	Normal (log transformed)

10.4.4 Deepwater eastern king prawn fishery

The mean catch rate of total bycatch (i.e., including monsters) in the deepwater eastern king prawn fishery was not significantly affected by the BRDs and TEDs that the fishers were using (Table 10.4.5). Mean catch rate of the targeted eastern king prawns was also unaffected by the devices (Table 10.4.5). However, when a BRD was used in conjunction with a TED, the mean catch rate of bycatch (i.e., excluding monsters) was significantly increased ($\boldsymbol{\beta}_2$ parameter estimate of 1.39). No measurements were obtained from this sector for nets that had the TED only.

Table 10.4.5. Mean catch rates of total bycatch, bycatch and target prawn species from the deepwater eastern king prawn fishery *Penaeus plebejus* based on 79 individual net tows obtained by opportunistically sampling on board fishing vessels. Generalised linear modelling was used to quantify the effects of codend type. Significant differences between treatments ($P < 0.05$) are bolded and identified by different alphabetic characters (A, B, C or D). The parameter estimates have been proportionally scaled so they can be compared to a standard net parameter value of 1. Standard errors in parentheses.

Response variable	**Mean observed catch rate in kg ha^{-1} from standard net**	**Generalised linear model parameter estimates (Proportionally scaled to a standard net parameter value of 1)**			**Distribution type**
		TED only	**BRD only**	**BRD and TED together**	
Total bycatch (includes monsters)	1.30 (0.19) A	-	1.00 (0.07) A	1.29 (0.03) A	Gamma
Bycatch (excludes monsters)	**1.28 (0.18) A**	**-**	**0.95 (0.05) A**	**1.39 (0.22) B**	**Normal (log transformed)**
Marketable Prawns	0.59 (0.07) A	-	1.03 (0.04) A	1.20 (0.13) A	Normal (log transformed)

10.4.5 North Queensland tiger/endeavour prawn fishery

Analyses of the 128 observations from the north Queensland tiger/endeavour prawn sector indicated that when the TEDs and BRDs were used together, they resulted in a significant reduction (9%) in a) total mean bycatch (i.e., including monsters) rate, b) mean bycatch (i.e., excluding monsters) rate, and c) mean prawn catch rate (β_2 parameter estimate of 0.91, Table 10.4.6). Note that no measurements were obtained from nets that had BRDs only or TEDs only, and therefore it was not possible to quantify these codend types in this particular sector. The only term that could be quantified was BRDs and TEDs together.

Table 10.4.6. Mean catch rates of total bycatch, bycatch and target prawn species *Penaeus latisulcatus, Penaeus semisulcatus, Metapenaeus endeavouri* and *Metapenaeus ensis* from the north Queensland tiger/endeavour prawn fishery based on 128 individual net tows obtained by opportunistically sampling on board fishing vessels. Generalised linear modelling was used to quantify the effects of codend type. Significant differences between treatments ($P < 0.05$) are bolded and identified by different alphabetic characters (A, B, C or D). The parameter estimates have been proportionally scaled so they can be compared to a standard net parameter value of 1. Standard errors in parentheses.

Response variable	**Mean observed catch rate in kg ha^{-1} standard net**	**Generalised linear model parameter estimates (Proportionally scaled to a standard net parameter value of 1)**			**Distribution type**
		TED only	**BRD only**	**BRD and TED together**	
Total Bycatch (includes monsters)	**4.64 (0.26) A**	**-**	**-**	**0.91 (0.02) B**	**Gamma**
Bycatch (excludes monsters)	**4.64 (0.26) A**	**-**	**-**	**0.91 (0.02) B**	**Gamma**
Marketable Prawns	**1.03 (0.08) A**	**-**	**-**	**0.91 (0.03) B**	**Gamma**

10.4.6 Scallop fishery

Analysis of the 139 bycatch measurements obtained in the saucer scallop fishery indicated that a) TEDs, b) BRDs and c) both devices used together all resulted in a significant reduction in mean total bycatch (including monsters) rate (Table 10.4.7). The predicted mean catch rate of total bycatch (i.e., including monsters) was 68% lower in nets with both a TED and BRD ($\boldsymbol{\beta}_2$ parameter estimate of 0.32, Table 10.4.7). Note the same level of reduction was achieved for the TED-only analysis. All codend types caught significantly less total bycatch (i.e., including monsters) compared to the standard net. Of all of the analyses undertaken with the opportunistic data, this was the largest reduction in total mean bycatch (i.e., including monsters) rate of any sector.

When large fauna (i.e., monsters) were excluded from the analyses, the model indicated a 31% reduction in mean bycatch rate in nets with both a TED and BRD ($\boldsymbol{\beta}_2$ parameter estimate of 0.69, Table 10.4.7). The parameter estimates indicated that most of the reductions in bycatch were due to the TED, and that the TED excluded more bycatch in saucer scallop fishery than BRDs. When the TEDs and BRDs were used together, they resulted in a significant (11%) reduction in the mean catch rate of scallops ($\boldsymbol{\beta}_2$ parameter estimate of 0.89, Table 10.4.7). Most of the reduction was due to the BRDs ($\boldsymbol{\beta}_2$ parameter estimate of 0.90, Table 10.4.7), while the TED only had no significant effect on mean scallop catch rate.

Table 10.4.7. Mean catch rates of total bycatch, bycatch and scallops from the Queensland saucer scallop *Amusium japonicum ballotti* fishery based on 139 individual net tows obtained by opportunistically on board fishing vessels. Generalised linear modelling was used to quantify the effects of codend type. Significant differences between treatments ($P < 0.05$) are bolded and identified by different alphabetic characters (A, B, C or D). The parameter estimates have been proportionally scaled so they can be compared to a standard net parameter value of 1. Standard errors in parentheses.

Response variable	Mean observed catch rate in kg ha^{-1} from Standard net	Generalised linear model parameter estimates (Proportionally scaled to a standard net parameter value of 1)			Distribution type
		TED only	BRD only	BRD and TED	
Total bycatch (including monsters)	**9.39 (1.02) A**	**0.32 (0.03) C**	**0.60 (0.14) B**	**0.32 (0.04) C**	**Normal (log transformed)**
Bycatch (excludes monsters)	**4.46 (0.59) A**	**0.68 (0.05) B**	**0.81 (0.13) AB**	**0.69 (0.06) B**	**Gamma**
Marketable Scallops	**3.00 (0.20) A**	**0.99 (0.01) A**	**0.90 (0.01) AB**	**0.89 (0.01) B**	**Normal (square-root transformed)**

10.5 DISCUSSION

Although maintaining experimental control is challenging when working on board vessels during their normal working operations, the data and analyses provide valuable information on the performance of the BRDs that are being used by the Queensland trawl fleet. The main findings from this chapter are:

1) When the prawn trawl sectors were pooled, no statistically significant reduction in total mean bycatch (i.e., including monsters) rate was detected due to TEDs or BRDs, together or by themselves (Table 10.4.3). When large bycatch species were omitted from the analysis, a statistically significant reduction of 25% in mean bycatch (i.e., excluding monsters) rate was detected when both devices were used together.
2) When the prawn trawl sectors were pooled, no significant effects on mean prawn catch rates were detected for TEDs and BRDs, by themselves or when used together.
3) In the north Queensland tiger/endeavour prawn fishery, mean bycatch rates declined significantly (by 9%, $\boldsymbol{\beta}_2$ parameter estimate of 0.91, Table 10.4.6) when TEDs and BRDs were used together, but a statistically significant equivalent reduction in mean prawn catch rate was also detected.
4) No significant reduction in mean bycatch rate was detected in the shallow water (Table 10.4.4) or deepwater (Table 10.4.5) eastern king prawn sectors, nor was there any significant effect on mean prawn catch rate in these sectors.
5) A 68% reduction in the total mean bycatch (i.e., including monsters) rate was obtained from the saucer scallop fishery when TEDs and BRDs were used together ($\boldsymbol{\beta}_2$ parameter estimate of 0.32, Table 10.4.7). The same reduction was obtained for the TED-only analysis. Significant bycatch reduction due to BRDs is occurring in the scallop fishery, but most is attributed to the TEDs.
6) A statistically significant reduction of 11% in the mean scallop catch rate was detected in nets with both a TED and BRD (Table 10.4.7). This loss of scallops was largely due to the BRDs that fishers were using.

The opportunistic sampling provided detailed information on catch rates directly from the fleet, but it was heavily dependent upon a) when the fishers allowed the researchers on board to obtain measurements and b) where the fishers chose to trawl. For the data and analyses to be of value, we have to assume that the data are representative of the fleet. While such assumptions can be made for the research charters (because the charters were specifically designed to be representative), we had very little control over the opportunistic sampling design. Also, the experimental design and control required for comparing nets with and without BRDs and TEDs was very limited. Fishers in Queensland are required to use a TED and one of seven recognised BRDs. In most cases, the objective for commercial fishers when choosing a suitable device is to minimise the loss of target species and bycatch reduction is of secondary importance.

The mean catch rate of marketable prawns in the eastern king prawn fishery was unaffected by TEDs and BRDs (Table 10.4.4 and Table 10.4.5). The mean bycatch rate was also largely unaffected. In contrast, the devices lowered marketable prawn catch rates in the north Queensland tiger/endeavour prawn fishery (Table 10.4.6). The fact that the reductions for prawns and bycatch occurred at the same rate (i.e., 9%) suggests that the devices being used were inefficient. That is, if efficient BRDs were used, it is reasonable to expect that bycatch reduction would have been higher than prawn loss. The fact that prawn loss and bycatch reduction were similar indicates that the TED and/or BRD were inadvertently allowing the passive loss of both bycatch and target species, rather than providing escape routes for bycatch species only.

The TEDs and BRDs used in the scallop fishery were more effective at reducing mean bycatch rate, with a concurrent small but significant reduction (11%) in mean scallop catch rate. The reduction in mean total bycatch rate was largely due to the TEDs and their interaction with large fauna. Large fauna make up approximately 64% of the bycatch weight in the scallop fishery, of which large sponges (Porifera) comprised 92% (Chapter 7). As such, TEDs were able to exclude the majority of the large fauna, resulting in a significant reduction in total mean bycatch rate. Interestingly, the regular exclusion of this large fauna did not result in a reduced mean scallop catch rate. Scallop loss can occur for two reasons. Firstly, the escape flap on the TEDs will continually open to exclude the large fauna, at which time scallops may also escape. Secondly, if an efficient TED is not used, large fauna may clog the TED, resulting in a build-up of catch and scallops in front of the device. At the completion of a trawl the accumulated catch can then either fall through the TED's escape hole or be forced forward through the mouth of the net. The fact that there was no significant reduction in scallop catch rate due to the TED (Table 10.4.7) suggests that commercial fishers were using relatively efficient devices in the scallop fishery.

10.6 REFERENCES

GenStat, 2005. GenStat, 8th ed. Lawes Agricultural Trust.

O'Neill, M.F., Courtney, A.J., Good, N.M., Turnbull, C.T., Yeomans, K.M., Staunton Smith, J., Shootingstar, C., 2005. Reference point management and the role of catch-per-unit effort in prawn and scallop fisheries. FRDC Project #1999/120 Final Report. Department of Primary Industries and Fisheries, Queensland QO 05001, p. 265.

11 An overview of the elasmobranch bycatch in the Queensland East Coast Trawl Fishery (Australia) and the effects of bycatch reduction devices

P. M. Kyne, A. J. Courtney, M. J. Campbell, K. E. Chilcott, S.W. Gaddes, C. T. Turnbull, C. C. van der Geest and M. B. Bennett

11.1 ABSTRACT

The Queensland East Coast Trawl Fishery (QECTF) is a complex multi-species and multi-sector fishery operating along Queensland's eastern coastline, with combined annual landings of about 10,000 tonnes. Elasmobranchs represent a relatively small but potentially ecologically significant component of bycatch in this fishery. At least 94 species of elasmobranchs occur in the managed area of the QECTF and half of these were recorded in the fishery's bycatch. Catch rates from the research charters indicated that elasmobranch bycatch was highly variable between sectors. Elasmobranch bycatch was extremely low in the north Queensland tiger/endeavour prawn fishery, low in the deepwater eastern king prawn fishery and moderate in the shallow water eastern king prawn and scallop fishery. The bycatch was dominated by one rhinobatid species (*Aptychotrema rostrata*) and two urolophids (*Trygonoptera testacea* and *Urolophus kapalensis*) in the shallow water eastern king prawn fishery, by one rajid species (*Dipturus polyommata*) and two scyliorhinids (*Asymbolus rubiginosus* and *Galeus boardmani*) in the deepwater eastern king prawn fishery, and by *A. rostrata* and two dasyatid stingrays (*Dasyatis kuhlii* and *D. leylandi*) in the scallop fishery. Significant reductions in the mean catch rate of *A. rostrata* and *A. rubiginosus* due to TEDs and BRDs were detected during two charters. Results from all of the charters were combined to give an overview of elasmobranch bycatch across the fishery. New information on elasmobranch distributions in Queensland waters is also presented.

11.2 INTRODUCTION

It is estimated that approximately half of the annual global catch of chondrichthyans (the cartilaginous fishes: elasmobranchs and holocephalans) is taken as bycatch (Stevens et al., 2000). As a consequence, some species of skates (Rajidae), sawfishes (Pristidae) and deepwater dogfishes (Centrophoridae and Squalidae) have been virtually extirpated from large areas (Stevens et al., 2000). In Australian waters, Graham et al. (2001) reported significant declines in catches of two dogfishes, *Centrophorus harrissoni* and *C. uyato*, together with skates and stingarees (Urolophidae) after 20 years of demersal fish trawling on the continental slope off New South Wales (NSW). Sharks and rays are also a regular component of the bycatch in Australia's Northern Prawn Fishery (Brewer 1999), where Stobutzki et al. (2001) identified 56 species and considered the unsustainability of stingray (Dasyatidae) and sawfish capture of particular concern.

The QECTF is a complex multi-species and multi-sector fishery, operating from Cape York in the north (10º30´ S, 142º30´ E) to the Queensland/NSW border (28º00´ S, 153º30´ E). This fishery is comprised of otter trawlers operating in coastal waters taking prawns (Penaeidae), scallops (*Amusium* spp.) and whiting (*Sillago robusta*); and beam trawlers targeting prawns in estuarine and inshore waters. The combined annual landings of the fishery are close to 10,000 t, with bycatch estimated to exceed 25,000 t (Robins and Courtney, 1999). The bycatch of elasmobranchs is known to vary considerably between fishery sectors. For example, in the Moreton Bay sector, elasmobranchs accounted for 15.4% of the bycatch by weight (Wassenberg and Hill, 1989) while in the banana prawn sector they represented less than 0.25% of the total bycatch (Stobutzki et al., 2001).

Bycatch reduction devices (BRDs) and turtle excluder devices (TEDs) were made mandatory throughout the otter trawl fishery between 2000 and 2002 and a bycatch reduction target of 40% was specified in the fishery's Management Plan [*Fisheries (East Coast Trawl) Management Plan 1999*]. Robins et al. (1999) and Broadhurst (2000) presented overviews of BRDs and TEDs employed in Australian prawn trawl fisheries. Seven BRDs are recognised in the Management Plan including the radial escape section, square mesh panel, fisheye, square mesh codend, bigeye, V-cut and the Popeye fishbox. A number of TED designs can also be used but all TED bar spacings are required to be no more than 12 cm apart. Little research has focused specifically on how BRDs and TEDs influence the capture of elasmobranchs. Robins-Troeger (1994) and Brewer et al. (1998) both highlighted the reduced capture of larger elasmobranchs, particularly batoids, in nets fitted with TEDs. However, while it is expected that the use of TEDs should greatly reduce the capture of larger elasmobranchs, the capture of smaller species and individuals may not be altered (Brewer, 1999).

This chapter describes the elasmobranch catch in various sectors of the QECTF and the effect BRDs and TEDs on their catch rates. While the project used both dedicated research charters and opportunistic sampling of the commercial vessels to sample the bycatch, this chapter presents results largely on the earlier. The species composition of elasmobranch bycatch in these sectors is presented, including new information on occurrence and distribution, and is discussed in the context of conservation and the management of biodiversity.

11.3 MATERIALS AND METHODS

Data on elasmobranchs sampled from the five research charters were analysed, specifically data from the:

1. shallow water eastern king prawn charter (Chapter 5)
2. north Queensland tiger/endeavour prawn charter (Chapter 6)
3. scallop charter (Chapter 7)
4. Hervey Bay whiting bycatch charter (Chapter 8)
5. deepwater eastern king prawn charter (Chapter 9).

In addition, elasmobranch species recorded from opportunistically sampling the bycatch of commercial vessels during their normal trawling activities in the eastern king prawn, tiger/endeavour prawn and scallop fisheries were also presented. Elasmobranch data from a previous FRDC-funded project (Project 96/257, Stobutzki et al., 2001), which includes a description of the bycatch from the Queensland banana prawn fishery, were also incorporated.

11.3.1 Recording catch rates

Details of the bycatch sampling methods can be found in the abovementioned chapters. In brief, all elasmobranchs sampled during the research charters were removed from the bycatch immediately after each trawl and later examined in the laboratory. Individuals were identified, weighed, sexed and measured. Total length (TL) and disc width (DW) were used as standard measurements.

11.3.2 Statistical methods

The effect of the TEDs and BRDs on catch rates of elasmobranchs were analysed using the same generalised linear modelling approaches as described in the previous chapters. Elasmobranch species catch rates were best modelled using a binomial distribution with a logit link function. The RPAIR procedure in GenStat, which performs t-tests for pairwise differences of means from a GLM, was used to test for significant differences in the probability of capture between net types. Due to their relatively low catch rates (i.e., high zero counts) it was not possible to undertake robust statistical tests for all elasmobranch species.

11.4 RESULTS

11.4.1 Elasmobranch bycatch

A total of 48 elasmobranch and one holocephalan species from 21 families were recorded from the bycatch, based on the present study results and those of Stobutzki et al. (2001) (Table 11.4.1). The most speciose families recorded were the whaler sharks (Carcharhinidae) with 12 species and the stingrays (Dasyatidae) with eight species.

The catch rate of elasmobranchs in the tiger/endeavour prawn charter (Chapter 6) was extremely low with only eight individuals from five species captured in the 192 samples. Elasmobranchs were captured in all codend types, however, the largest two individuals, a *Himantura toshi* (505 mm DW) and a *Rhynchobatus australiae* (420 mm DW) were captured in standard nets.

A total of 23 individuals from eight species were captured in the 96 samples during the Hervey Bay charter (Chapter 8). The blue-spotted maskray *Dasyatis kuhlii* (n = 8), and the Australian butterfly ray *Gymnura australis* (n = 5), were the most commonly recorded species. The two largest individuals, *Himantura toshi* with 520 mm and 730 mm DW, were captured in nets without TEDs, however a *G. australis* of 620 mm DW was captured in a net fitted with a TED.

Twelve species of elasmobranchs were recorded from the 120 samples undertaken in the shallow water eastern king prawn charter (Chapter 5) totalling 409 individuals. Elasmobranchs were recorded from 84 of the 120 samples in this sector (Figure 11.4.1). The species composition was dominated by three species, *Aptychotrema rostrata* (Rhinobatidae), *Trygonoptera testacea* (Urolophidae) and *Urolophus kapalensis* (Urolophidae), which together represented 91.9% of the elasmobranch catch by number, and 79.1% by mass (Table 11.4.2). *Aptychotrema rostrata* was recorded from 66 of the 120 trawl measurements (Figure 11.4.1b) and urolophids from 30 of the 120 trawl measurements (Figure 11.4.1c).

Table 11.4.1. Elasmobranch species recorded in the QECTF bycatch based on results from the present study and those Stobutzki et al. (2001). BP, banana prawn; EKP, eastern king prawn; HB, Hervey Bay; SC, scallop; TE, northern tiger/endeavour prawn.

Family	**Species**	**Fishery Sector**
Heterodontidae	*Heterodontus galeatus*	EKP
Parascylliidae	*Parascyllium collare*	EKP
Brachaeluridae	*Heteroscyllium colcloughi*	EKP
Orectolobidae	*Orectolobus maculatus*	EKP
Hemiscylliidae	*Chiloscyllium punctatum*	SC, TE
	Hemiscyllium ocellatum	TE
Scyliorhinidae	*Asymbolus analis*	EKP
	Asymbolus rubiginosus	EKP
	Atelomycterus sp. 1 [Jacobsen & Bennett]	SC
	Galeus boardmani	EKP
Triakidae	*Mustelus* sp. C [White]	EKP
Hemigaleidae	*Hemigaleus australiensis*	HB, SC, TE
Carcharhinidae	*Carcharhinus altimus*	BP
	Carcharhinus brevipinna	BP
	Carcharhinus dussumieri	BP
	Carcharhinus leucas	BP
	Carcharhinus limbatus	BP
	Carcharhinus macloti	BP
	Carcharhinus melanopterus	TE
	Carcharhinus sorrah	BP
	Carcharhinus tilstoni	TE
	Loxodon macrorhinus	SC
	Rhizoprionodon acutus	BP
	Rhizoprionodon taylori	BP
Sphyrnidae	*Eusphyra blochii*	BP
	Sphyrna lewini	BP
Pristidae	*Pristis zijsron*	BP
Rhynchobatidae	*Rhynchobatus australiae*	BP, SC, TE
Rhinobatidae	*Aptychotrema rostrata*	EKP, HB, SC
	Trygonorrhina sp. A [Last & Stevens, 1994]	EKP
Hypnidae	*Hypnos monopterygius*	EKP
Rajidae	*Dipturus australis*	EKP
	Dipturus polyommata	EKP
Urolophidae	*Trygonoptera testacea*	EKP
	Urolophus kapalensis	EKP
	Urolophus sufflavus	EKP
Dasyatidae	*Dasyatis fluviorum*	BP
	Dasyatis kuhlii	EKP, HB, SC, TE
	Dasyatis leylandi	BP, HB, SC, TE
	Dasyatis thetidis	EKP
	Himantura sp. A [Last & Stevens, 1994]	SC, HB
	Himantura toshi	BP, SC, TE
	Himantura uarnak	BP
	Himantura undulata	BP, SC
Gymnuridae	*Gymnura australis*	BP, EKP, HB, SC
Myliobatidae	*Aetomylaeus nichofii*	HB
Rhinopteridae	*Rhinoptera* spp.	BP
Chimaeridae*	*Hydrolagus lemures*	EKP

* Holocephali

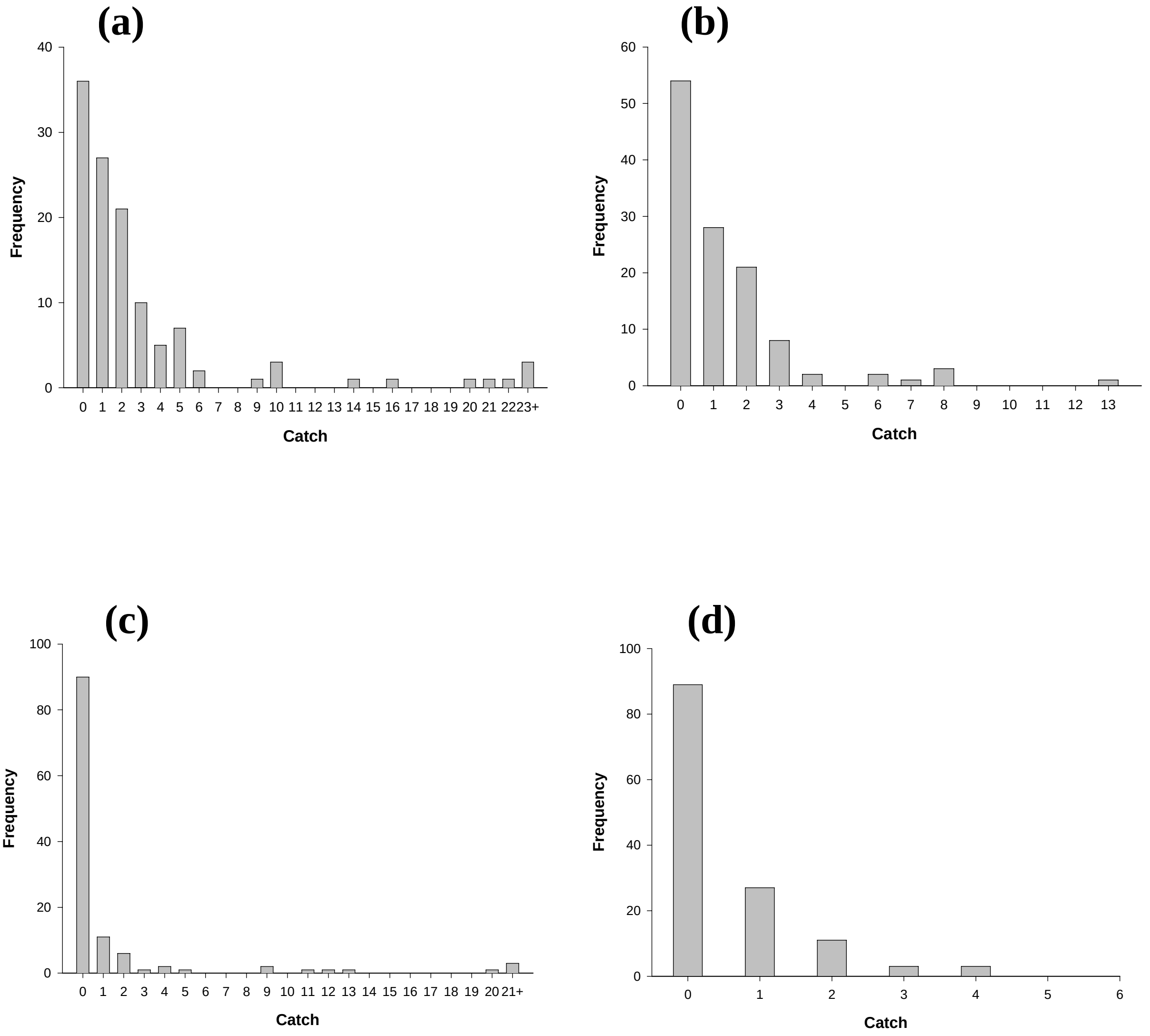


Figure 11.4.1. Catch-frequency distributions of elasmobranchs captured in the eastern king prawn sector. (a) All species, shallow water component; (b) *Aptychotrema rostrata*, shallow water component; (c) Urolophids combined, shallow water component; (d) All species, deep water component.

The generalised linear model predicted probabilities of capturing *A. rostrata* and urolophids in a two-nautical mile trawl in the shallow water eastern king prawn fishery sector are provided in Table 11.4.3. There were no significant effects due to codend treatment type for either *A. rostrata* or the urolophids. The catch of *A. rostrata* from all net types during the survey was dominated by immature individuals in the size range 360–460 mm TL (Figure 11.4.2a). Urolophids (*T. testacea* and *U. kapalensis*) were dominated by individuals in the size range 240–320 mm TL (Figure 11.4.2b).

Table 11.4.2. Elasmobranch bycatch from the shallow water eastern king prawn charter.

Species	**Common name**	**Number**	**% Catch**	**Mass (kg)**	**% Mass**
Aptychotrema rostrata	Eastern shovelnose ray	158	38.63	52.51	40.13
Trygonoptera testacea	Common stingaree	156	38.14	38.93	29.75
Urolophus kapalensis	Kapala stingaree	62	15.16	12.06	9.21
Dasyatis kuhlii	Blue-spotted maskray	12	2.93	7.75	5.92
Heterodontus galeatus	Crested horn shark	4	0.98	8.30	6.34
Hypnos monoterygius	Coffin ray	4	0.98	3.83	2.93
Trygonorrhina sp. A*	Eastern fiddler ray	3	0.73	0.75	0.57
Orectolobus maculatus	Spotted wobbegong	3	0.73	0.72	0.55
Heteroscyllium colcloughi	Bluegray carpetshark	2	0.49	4.55	3.48
Asymbolus analis	Grey spotted catshark	2	0.49	0.74	0.57
Asymblous rubiginosus	Orange-spotted catshark	2	0.49	0.53	0.41
Mustelus sp. C#	--	1	0.24	0.18	0.14
Total:		**409**		**130.85**	

* [Last and Stevens, 1994]; # [White]

Table 11.4.3. Predicted probabilities of capturing the eastern shovelnose ray (*Aptychotrema rostrata*) and urolophids (*Trygonoptera testacea* and *Urolophus kapalensis*) based on 120 trawls undertaken during the shallow water eastern king prawn charter. Standard errors in parenthesis.

Codend treatment type	**Probability of capture** ***Aptychotrema rostrata***	**Urolophids**
Standard	0.56040 (0.0792)	0.2265 (0.0401)
BRD	0.5634 (0.0915)	0.2554 (0.0509)
TED	0.6110 (0.0673)	0.2744 (0.0405)
BRD + TED	0.4825 (0.0567)	0.2456 (0.0451)

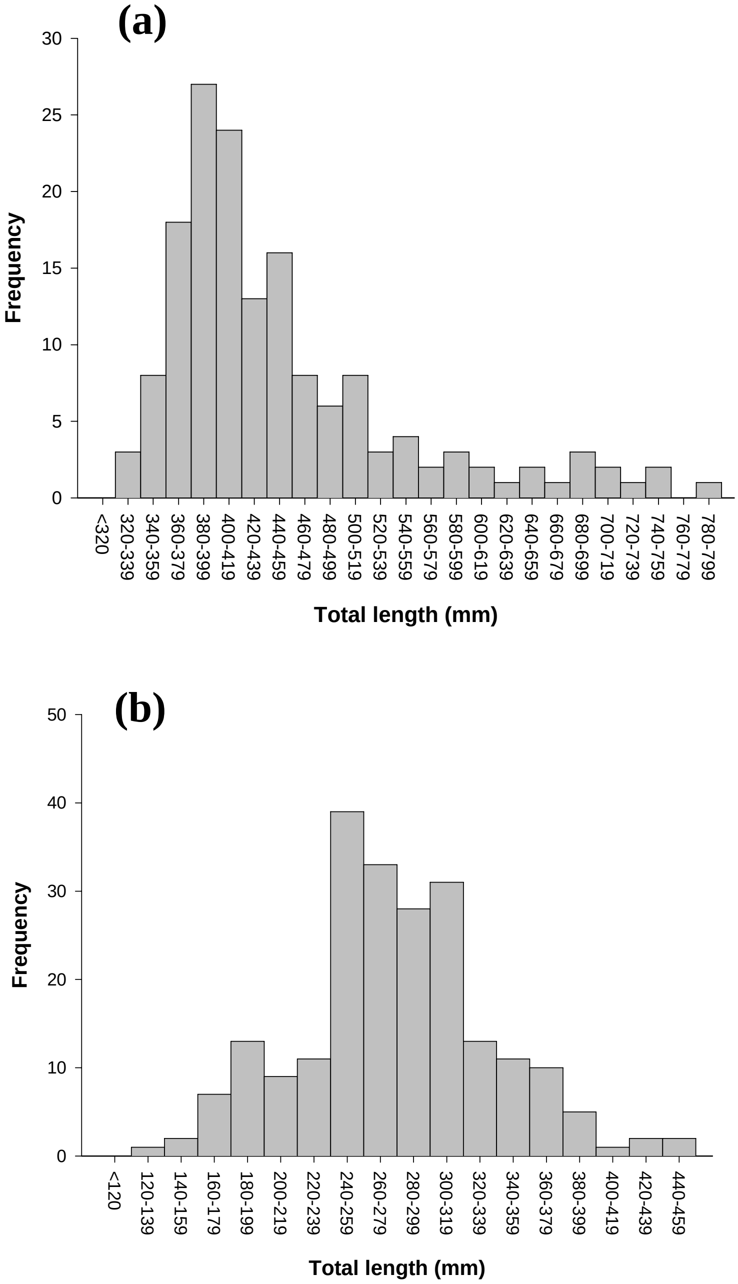


Figure 11.4.2. Size-frequency distributions of elasmobranchs captured during the shallow water eastern king prawn charter. (a) *Aptychotrema rostrata*; (b) Urolophids combined (*Trygonoptera testacea* and *Urolophus kapalensis*).

Nine elasmobranch and one holocephalan species were recorded from the 130 samples undertaken during the deepwater eastern king prawn charter (Chapter 9) totalling 65 individuals. Elasmobranchs were recorded from 41 of the 130 samples (Figure 11.4.1d). The species composition was dominated by *Dipturus polyommata* (Rajidae), *Asymbolus rubiginosus* (Scyliorhinidae) and *Galeus boardmani* (Scyliorhinidae), which together represented 83.5% of the catch by number and

64.6% by mass (Table 11.4.4). Individuals captured were generally small, with only five elasmobranchs weighing ≥ 500 g. Generalised linear modelling revealed a significant difference between codend treatment types for *A. rubiginosus,* but not for *D. polyommata* or *G. boardmani* (Table 11.4.5).

Table 11.4.4. Elasmobranch bycatch from the deepwater eastern king prawn charter.

Species	**Common name**	**Number**	**% Catch**	**Mass (kg)**	**% Mass**
Dipturus polyommata	Argus skate	23	35.83	4.40	21.3
Asymbolus rubiginosus	Orange-spotted catshark	20	30.77	6.20	30.0
Galeus boardmani	Sawtail shark	11	16.92	2.75	13.3
Asymbolus analis	Grey spotted catshark	4	6.15	0.55	2.7
Hypnos monopterygius	Coffin ray	2	3.08	0.35	1.7
Aptychotrema rostrata	Eastern shovelnose ray	1	1.54	1.30	6.3
Dasyatis thetidis	Black stingray	1	1.54	2.50	12.1
Trygonoptera testacea	Common stingaree	1	1.54	0.30	1.5
Urolophus sufflavus	Yellowback stingaree	1	1.54	0.30	1.5
*Hydrolagus lemures**	Blackfin ghostshark	1	1.54	2.00	9.7
Total:		**65**		**20.65**	

* Holocephali

Table 11.4.5. Predicted probabilities of capturing the orange-spotted catshark (*Asymbolus rubiginosus*), the argus skate (*Dipturus polyommata*) and the sawtail shark (*Galeus boardmani*) based on 130 trawls undertaken during the deepwater eastern king prawn charter. Standard errors in parenthesis.

Codend	**Probability of capture**		
treatment type	*Asymbolus rubiginosus*	*Dipturus polyommata*	*Galeus boardmani*
Standard	0.4154 (0.0031)	0.1684 (0.0779)	0.0504 (0.0346)
BRD	0.0154 (0.00002)	0.2361 (0.0539)	0.0748 (0.0289)
TED	0.4154 (0.0022)	0.1378 (0.0310)	0.0623 (0.0432)
BRD + TED	0.0154 (0.0001)	0.2214 (0.0368)	0.0791 (0.0254)

Eleven elasmobranch species were recorded from the 236 trawl measurements undertaken during the scallop charter (Chapter 7) totalling 205 individuals. Elasmobranchs were recorded from 100 of the 236 trawl measurements. The species composition was dominated by *Aptychotrema rostrata* (Rhinobatidae), *Dasyatis kuhlii* and *D. leylandi* (Dasyatidae), which together represented 91.2% of the catch by number and 60.9% by mass (Table 11.4.6.). A single large (1330 mm DW) leopard whipray *Himantura undulata* represented 20.9% of the elasmobranch catch by mass. Generalised linear modelling revealed a significant effect in catch rates due to codend treatment type for the *A. rostrata*, but not for *D. kuhlii* or *D. leylandi* (Table 11.4.7).

Table 11.4.6.. Elasmobranch bycatch from the scallop fishery charter**.**

Species	**Common name**	**Number**	**% Catch**	**Mass (kg)**	**% Mass**
Aptychotrema rostrata	Eastern shovelnose ray	107	52.20	72.47	37.82
Dasyatis kuhlii	Blue-spotted maskray	48	23.41	37.11	19.36
Dasyatis leylandi	Painted maskray	32	15.61	7.20	3.76
Rhynchobatus australiae	White-spotted guitarfish	8	3.90	12.82	6.69
Chiloscyllium punctatum	Grey carpetshark	3	1.46	5.20	2.71
Gymnura australis	Australian butterfly ray	2	0.98	5.49	2.86
Loxodon macrorhinus	Sliteye shark	1	0.49	1.50	0.78
Hemigaleus australiensis	Australian weasel shark	1	0.49	0.47	0.24
Himantura sp. A*	Brown whipray	1	0.49	0.89	0.47
Himantura toshi	Black-spotted whipray	1	0.49	8.50	4.44
Himantura undulata	Leopard whipray	1	0.49	40.00	20.87
Total:		**205**		**191.65**	

* [Last and Stevens, 1994]

Table 11.4.7. Predicted probabilities of capturing the eastern shovelnose ray (*Aptychotrema rostrata*), the blue-spotted maskray (*Dasyatis kuhlii*) and the painted maskray (*Dasyatis leylandi*) based on 236 trawls undertaken during the scallop fishery charter. Standard errors in parenthesis.

Codend treatment type	**Probability of capture** *Aptychotrema rostrata*	*Dasyatis kuhlii*	*Dasyatis leylandi*
Standard	0.2694 (0.0362)	0.1509 (0.0309)	0.1540 (0.0387)
BRD	0.3582 (0.0322)	0.1363 (0.0318)	0.0851 (0.0356)
TED	0.2136 (0.0308)	0.1506 (0.0313)	0.1067 (0.0337)
BRD + TED	0.1934 (0.0327)	0.1208 (0.0309)	0.1273 (0.0362)

11.4.2 New information on the occurrence of elasmobranchs

Samples collected from research charters provided new information of the occurrence and distribution of several species in Queensland waters. The grey spotted catshark *Asymbolus analis* was recorded for the first time from Queensland, the Sydney skate *Dipturus australis* was confirmed from the state, and significant southern range extensions were documented for the painted maskray *Dasyatis leylandi* and the banded eagle ray *Aetomylaeus nichofii*.

Asymbolus analis was trawled from the shallow and deep water sectors of the eastern king prawn fishery, at depths of 85–159 m. The species is endemic to the east coast of Australia, and was previously thought to be confined to New South Wales and Victorian waters from Port Macquarie south to Lakes Entrance. Records collected in the present study provide the first account of *A. analis* from Queensland waters. *Asymbolus* includes eight species restricted to Australian waters (Last, 1999) and an undescribed species from New Caledonia (Séret, 1994). Further information on the taxonomy and life history of the species in Queensland waters is provided in Kyne et al. (2005).

A specimen of *D. australis* was captured in the deepwater eastern king prawn fishery in 135 m. The individual was deposited in the Queensland Museum and represents the third specimen from Queensland held there. *Dipturus australis* is reported to be ”the most common skate on the continental shelf of central eastern Australia” (Last and Stevens, 1994), being recorded from off Moreton Bay south to Jervis Bay, New South Wales. Last and Stevens (1994: 347) state that “records of this species from prawn trawl catches from southern Queensland require validation”. This specimen, taken by a commercial prawn trawler, confirms that the Queensland trawl fishery interacts with this species. Despite its apparent common occurrence off New South Wales, this species appears to be uncommon in Queensland waters.

Two specimens of *Dasyatis leylandi* were captured during the Hervey Bay charter at a depth of 11 m. These records represent a significant new southern range extension for the species on the east coast of Australia (about 1200 km), having previously been recorded from northern Australia between Monte Bello Islands, Western Australia and Townsville, Queensland, as well as New Guinea (Last and Stevens, 1994). The species appears to be relatively common on the scallop trawling grounds between Hervey Bay and Gladstone.

A specimen of *Aetomylaeus nichofii* was captured during the Hervey Bay charter at a depth of 8 m. Last and Stevens (1994) report that *A. nichofii* has an Indo-West Pacific distribution from southern Japan to Australia and west to India. In Australia it was reported in tropical waters from Bonaparte Archipelago, Western Australia to Cairns, Queensland. The Hervey Bay specimen significantly expands the previously documented southern range of the species on the east coast of Australia (by ~1600 km).

Further information on the above new records as well the biogeography of other Queensland elasmobranchs is provided in Kyne et al. (2005).

11.5 DISCUSSION

At least 94 elasmobranch and two holocephalan species occur in the managed area of the QECTF (Last and Stevens, 1994). Half of these species were recorded in the trawl bycatch, based on data considered herein. Results indicate that elasmobranch bycatch is variable between sectors, with the highest catch rates in the eastern king prawn sector. While TEDs are likely to reduce the capture of large elasmobranchs (Brewer, 1999) preliminary results suggest that neither TEDs nor BRDs are impacting upon the retention of small individuals and species.

Codend type (i.e., Standard codend, BRD, TED, or BRD+TED) did not significantly affect the capture of *A. rostrata* (commonly to 850 mm TL), *T. testacea* (to 450 mm TL) or *U. kapalensis* (to 360 mm TL) – all relatively small species in the shallow water eastern king prawn fishery. Furthermore, codends fitted with TEDs actually had the highest predicted probability of *A. rostrata* capture, and standard codends (no TED or BRD) had the lowest probability of capturing urolophids. However, it needs to be noted that these differences were not significant. The fact that urolophids were often captured in aggregations may have influenced these results.

As female *A. rostrata* are known to mature at 540–660 mm TL and males at 600–680 mm TL (Kyne and Bennett, 2002), the majority of individuals captured during the shallow water eastern king prawn charter were immature. In contrast, both urolophid species (males and females) appear to mature at between 230–270 mm TL (Kyne, unpublished data), indicating that a considerable proportion of mature individuals were captured. The opportunistic sampling also revealed high catches of neonates at certain times of the year, resulting in high levels of trawl-induced juvenile mortality. Furthermore, gravid female *T. testacea* often abort near-term embryos after capture. While *A. rostrata* appears to be a hardy species, usually capable of surviving trawling, urolophids appear to have lower survivability (unpublished information on capture mortality and survivability). Therefore, high rates of mortality at all life stages may have negative impacts on the viability of urolophid populations. Data from the South East Trawl Fishery in New South Wales support this suggestion, where after 20 years of fishing the capture of four urolophid species has suffered a 45–90% reduction depending on area (Graham et al., 2001).

One species of particular concern that has been recorded as bycatch in the QECTF is the bluegray carpetshark *Heteroscyllium colcloughi*. This species is listed as Vulnerable on the IUCN Red List of Threatened Species and occupies a restricted range centred in south-east Queensland, which receives high fishing effort in the eastern king prawn fishery. Prawn trawl bycatch is considered one of the most important threatening processes acting upon this species (Pogonoski et al., 2002). A total of six individuals of this species have been recorded from both charters and opportunistic sampling during the present study, including a female of 670 mm TL captured in a net fitted with a TED (the species is reported to 850 mm TL).

Australia has recently released its draft National Plan of Action for the Conservation and Management of Sharks which highlights the need to reliably assess the bycatch of elasmobranchs in Australian fisheries and undertake research into bycatch reduction techniques. The project is attempting to meet these needs in the QECTF and will provide the first information on elasmobranch bycatch in many sectors of the fishery.

11.6 REFERENCES

Brewer, D., Rawlinson, N., Eayrs, S., Burridge, C., 1998. An assessment of by-catch reduction devices in a tropical Australian prawn trawl fishery. Fish. Res. 36, 195-215.

Brewer, D. 1999. Northern Prawn Fishery status report. In: Buxton, C., Eayrs, S., (Eds.) Establishing meaningful targets for by-catch reduction in Australian fisheries, Hobart, 24-25 September 1998. Australian Society for Fish Biology, Sydney. pp. 11-23.

Broadhurst, M.K., 2000. Modifications to reduce by-catch in prawn trawls: a review and framework for development. Rev. Fish Biol. Fish. 10, 27-60.

Department of Agriculture, Fisheries and Forestry, Australia (AFFA), 2002. The Australian National Plan of Action for the Conservation and Management of Sharks. Public Consultation Draft. AFFA, Canberra.

GenStat 7th ed., 2003. Lawes Agricultural Trust.

Graham, K.J., Andrew N.L., Hodgson, K.E., 2001. Changes in relative abundance of sharks and rays on Australian South-East Fishery trawl grounds after twenty years of fishing. Mar. Freshw. Res. 52, 549-561.

Kyne, P.M., Bennett, M.B., 2002. Reproductive biology of the eastern shovelnose ray, *Aptychotrema rostrata* (Shaw and Nodder, 1794), from Moreton Bay, Queensland, Australia. Mar. Freshw. Res. 53, 583-589.

Kyne, P.M., Johnson, J.W., Courtney, A.J., Bennett, M.B., 2005. New biogeographical information on Queensland chondrichthyans. Mems. Qld. Mus. 50(2), 321-327.

Last, P.R. (ed.), 1999. Australian catsharks of the genus *Asymbolus* (Carcharhiniformes: Scyliorhinidae). CSIRO Mar. Lab. Rpt. 239.

Last, P.R., Stevens, J.D., 1994. Sharks and rays of Australia. CSIRO Publishing, Melbourne.

Pogonoski, J.J., Pollard, D.A., Paxton, J.R., 2002. Conservation overview and action plan for Australian threatened and potentially threatened marine and estuarine fishes. Environment Australia, Canberra.

Robins-Troeger, J.B., 1994. Evaluation of the Morrison soft turtle excluder device: prawn and by-catch variation in Moreton Bay, Queensland. Fish. Res. 19, 205-217.

Robins, J.B., Courtney, A.J., 1998. Status report on bycatch within the Queensland Trawl Fishery. In: Buxton, C., Eayrs, S., (Eds.), Establishing meaningful targets for bycatch reduction in Australian fisheries, Hobart, 24-25 September 1998. Australian Society for Fish Biology, Sydney. pp. 24-45.

Robins, J.B., Campbell, M.J., McGilvray, J.G., 1999. Reducing prawn-trawl by-catch in Australia: an overview and an example from Queensland. Mar. Fish. Rev. 61(3), 46-55.

Séret, B., 1994. Chondrichthyan fishes of New Caledonia. Chondros 5(3), 6-9.

Stevens, J.D., Bonfil, R., Dulvy, N.K., Walker, P.A., 2000. The effects of fishing on sharks, rays, and chimaeras (chondrichthyans), and the implications for marine ecosytems. ICES J. Mar. Sci. 57, 476-494.

Stobutzki, I.M., Blaber, S., Brewer, D., Fry, G., Heales, D., Miller, M., Milton, D., Salini, J., Van der Velde, T., Wassenberg, T., Jones, P., Wang, Y., Dredge, M., Courtney, A., Chilcott, K. and Eayrs, S., 2001. Ecological sustainability of by-catch and biodiversity in prawn trawl fisheries. FRDC Project Report 1996/257.

Wassenberg, T. J., Hill, B.J., 1989. The effect of trawling and subsequent handling on the survival rates of the by-catch of prawn trawlers in Moreton Bay, Australia. Fish. Res. 7, 99-110.

12 Objective 4. Review the known biology and distribution of all recently approved “permitted fish” species associated with the trawl fishery.

J. A. Haddy

12.1 INTRODUCTION

Recent changes in the management plan of Queensland East Coast Trawl Fishery (QECTF) allow commercial fishers to retain non-target byproduct species. These species include barking crayfish (*Linuparus trigonus*), Balmain bugs (*Ibacus* spp.), three spot crabs (*Portunus sanguinolentus*), mantis shrimps, (Stomatopoda), cuttlefish (*Sepia* spp.), octopus (*Octopus* spp.), pipehorses (*Solegnathus* spp.) and pinkies (*Nemipterus* spp.). Several of these groups consist of numerous species and currently there is no available information on the catch composition and abundance of these species within the fishery. Individual log records of these species have only recently been introduced. These records for 2000 to 2002 are shown in Figure 12.1.1. Despite the obvious economic importance these species contribute to the overall value of the QECTF very little research has been conducted on their biology and or sustainable management.

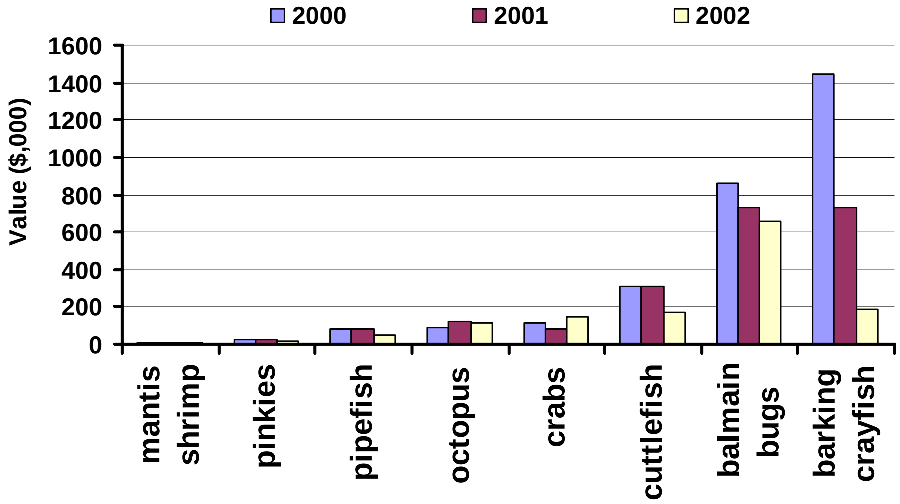


Figure 12.1.1 Approximate value of “permitted species” based on reported logbook landings from 2000 – 2002

The following review outlines the known biology of these recently permitted species. Please note that a report on the Queensland sand crab fishery is currently being compiled and to avoid unnecessary duplication, the biology of sand crabs has not been reviewed here. Readers should therefore refer to the following reviews, Chaplin et al., (2001), Melville-Smith et al., (2001), Potter et al., (2001), Sumpton et al., (2002) for information on sand crabs.

*12.1.1 Barking crayfish (*Linuparus trigonus*)*

Barking crayfish, also known as spear or champagne lobsters, are one of three extant species of the genus *Linuparus* and belong to one of eight genera of the Palinuridae family (spiny lobsters) (Holthuis 1991). They are a deepwater lobster inhabiting waters from 81 to 313 m, and are distributed in the Indo-Pacific region, including Japan, Taiwan, Philippines and eastern and western Australia. There is some evidence that shows that these lobsters may live in burrows as their catch rates have been shown to display diel variability, and fossil records indicate that *Linuparus* species are associated with burrows (Bishop and Williams, 1986). Off Townsville *Linuparus trigonus* occur in sufficient densities to support a commercial fishery. The fishery is confined to a small, well-defined area of the continental slope, about 70 km by 20 km in area. With the development of an export market for barking crayfish several fishers have targeted this deepwater species over recent years. This increase in fishing effort for the species has resulted in a marked increase in landings and during 2000 an estimated 100 tonnes were landed worth approximately $1.4 million dollars (QFS Logbook data). However despite the economic importance of this resource very little is known about the biology of *L. trigonus*.

Planurid lobsters exhibit five major phases within the life cycle: adult, egg, phyllosoma (larval stages), puerulus (postlarval stage) and juvenile (Lipicus and Cobb, 1994). Fertilisation is external whereby the male deposits a spermatophoric mass on the female’s sternum. The female rasps the spermatophoric mass prior to spawning to release sperm for fertilising the eggs as they are extruded onto the abdomen and pleopods. The female then carries the egg mass on her abdomen where they develop and hatch as a phyllosoma larvae, which disperse offshore to develop over a long oceanic larval phase prior to settling as post larvae. The first larval stage of *Linuparus* species hatch in a more advanced condition than other planurid lobsters, which indicates that the larval phase has been shortened in these deepwater species (Baisre, 1994), however the duration and total number of the larval phases in *Linuparus* species is currently unknown. Anecdotal evidence indicates that the catch rates of small lobsters increase with depth. This trend indicates that barking crayfish settle in deep water and move to shallower water as they grow (Ward, unpublished data).

There are only two detailed biological studies on *L. trigonus*. Kim (1977) studied gametogenesis and early development of *L. trigonus* from Asian waters. This study demonstrated that these lobsters have an annual reproductive cycle that can be classified into four successive stages: multiplication stage from September to December, growing stage from January to March, maturation division stage from April to May, and mature stage from June to August. Spawning took place from May to August with a peak of activity from late July to early August. Wassenberg and Hill (1989) investigated the diet of *L. trigonus* and demonstrated that these lobsters were predators of slow moving or near sessile benthic invertebrates, with its diet consisting mainly of bivalves, gastropods, ophiuroids, crustaceans, polychaetes and foraminiferans.

The lack of information on this species highlights that more research is needed to ensure that this byproduct fishery is properly developed and sustainable. Research activities should be centred on obtaining an understanding of the reproductive capacity of the Queensland population and growth rates in *L. trigonus*.

12.1.2 Balmain bugs, Ibacus *spp.*

Balmain bugs are marine lobsters of the genus *Ibacus* and belong to the family Scyllaridae. There are eight species of Balmain bugs and five of these species are known to occur in Queensland waters: *I. alticrenatus, I. brevipes, I. brucei, I. chacei* and *I. peronii* (Brown and Holthuis, 1998). The distributions, depth range and maximum sizes of Queensland's *Ibacus* species are shown in Table 12.1.1. Balmain bugs typically inhabit soft bottom substrates such as sand, mud and clay, which allow them to dig into the substrate and cover themselves (Holthuis, 1991). Captive studies on *I. peronii* indicated that both locomotion and feeding are nocturnal activities and that during the day animals remain buried in the substrate (Suthers and Anderson, 1981). Their diet consists of small benthic invertebrates and animal remains (Suthers and Anderson, 1981).

Table 12.1.1. Distributions, depth ranges and maximum sizes of Queensland's *Ibacus* species

Species	Max size CL (mm)	Depth (m)	Distribution
I. alticrenatus	63	82-686	South of the Coral Sea
I. brevipes	45	186-457	North of the Coral Sea
*I. brucei**	72	83-559	South of Central QLD
*I. chacei**	76	22-330	South of Innisfail
I. peronii	86	4-288	South of Moreton Bay

* Indicates the major species harvested in Queensland

As with spiny lobsters, *Ibacus* species carry their eggs on the pleopods underneath the abdomen. Newly deposited eggs of *I. peronii* are bright orange and spherical. During incubation the eggs develop two black eye-spots and as hatching approaches egg colour changes to a brown colour with two enlarged eye-spots (Stewart et al., 1997). Observations by Stewart et al. (1997) on captive berried *I. peronii* indicated the incubation period lasted between three to four months. Female *I. peronii* and *I. chacei* reach sexual maturity at a carapace length of approximately 50 mm and 54 mm respectively. Fecundity estimates of *Ibacus* spp. have only been determined for *I. peronii* and range from 5000 to 37,000 eggs (Stewart et al., 1997). *I. peronii* hatch as an actively swimming pre-phyllosomata that transforms into a phyllosoma within 15 to 20 minutes by unfolding the swimming legs (Stewart et al., 1997). Newly hatched and unfolded phyllosoma larvae are flattened and transparent and range in size from 2.6–3 mm in total length, depending on species (Ritz and Thomas, 1973). The larvae then undergo 7–8 moults prior to metamorphosing into nisto (= puerulus in Palinurids) larvae (Ritz and Thomas, 1973; Takahashi and Saisho, 1978; Atkinson and Boustead, 1982). The nisto larva is a transitory stage between the planktonic phyllosoma and the benthic juveniles. Successful rearing experiments on *Ibacus* spp. indicate that larvae reach the nisto stage within 65–76 days (Takahashi and Saisho, 1978; Mikami and Takashima, 1993) and stay in this stage for a further 21–26 days before moulting into juveniles (Takahashi and Saisho, 1978; Atkinson and Boustead, 1982). These periods indicate that the planktonic phase of *Ibacus* spp. would require at least three months at sea.

Very little biological information is available for Queensland's *Ibacus* species. *I. chacei* and *I. brucei* appear to be the dominant Balmain bugs caught in the QECTF, however some commercial fishers report catching commercial quantities of *I.*

alticrenatus. Data from tag/recapture studies in NSW on *I. peronii* and *I. chacei* indicated that *I. peronii* exhibited a classic nomadic pattern of movement and that *I. chacei* underwent a long northward migration (Stewart and Kennelly, 1998). This movement combined with the fact that reproductively active animals are not found off the New South Wales coast indicates that *I. chacei* migrates to spawn off the Queensland coast, with the larvae being distributed in a southerly direction via the East Australian current.

Ibacus peronii and *I. chacei* are the only species of Balmain bugs in which growth has been studied. Stewart and Kennelly (2000) showed that smaller individuals of both *Ibacus* species displayed a higher moulting frequency and larger moult increments than larger individuals. The von Bertalanffy growth parameters L_∞ and K estimated by Stewart and Kennelly (2000) for *I. chacei* and *I. peronii* are given in Table 12.1.2, the size at age zero was set at 12.2 mm.

Table 12.1.2. von Bertalanffy growth parameter estimates for *I. peronii* and *I. chacei*

Parameter	***Ibacus peronii***		***Ibacus chacei***	
	♂	♀	♂	♀
L_∞	64.8	81.1	72.8	71.9
K	0.504	0.431	0.440	0.730

Kennelly and Stewart (2000) showed that growth was rapid in the first four years but dramatically slowed thereafter indicating that male and female *I. peronii* reached their $L_{\max}$ between 7 and 18 years and 5 and 11 years respectively, whereas *I. chacei* reached their $L_{\max}$ between 4 and 7 years (sexes combined). However, caution should be noted for the population estimates for *I. chacei* in this study, as only 37 animals were used in the analysis and that the maximum observed size was considerably lower than the known maximum size of *I. chacei*.

*12.1.3 Three spot crabs (*Portunus sanguinolentus*)*

The three spot crab, *Portunus sanguinolentus* is distributed throughout the Indo-West Pacific region and typically inhabits sandy oceanic habitats to a depth of 30 metres (Sumpton et al., 1989). These crabs belong to the family Portunidae and are closely related to the sandcrab *Portunus pelagicus*. Portunid crabs form extensive fisheries around the world and a substantial amount is known about their biology. Three spot crabs are primarily predators of slow moving or sessile benthic macro-invertebrates such as bivalves and crabs, however fish remains, algae and other decaying material has also been reported in the diet of this crab (Wu and Shin, 1998, Sukumaran and Neelakantan, 1997a). As a result these crabs are likely to play an important role in consuming the discarded bycatch (Wassenberg and Hill, 1982).

The life cycle of three spot crabs involves five phases: egg, zoea, megalopa, juvenile and adult. Male and female three spot crabs mature between 74 and 90 mm depending on geographical locality (Campbell and Fielder, 1986, Sukumaran and Neelakantan, 1996; Sumpton et al., 1989; Sarada, 1998). Sumpton et al., (1989) reported that the smallest sexually mature male and female three spot crabs had carapace widths of 83 and 74 mm respectively (Sumpton et al., 1989). Similarly, Campbell and Fielder

(1986) demonstrated that female three spot crabs reached their first maturity instar moult at carapace widths of 75-115 mm. Continuous year-round spawning has been reported in Hawaiian and Indian populations of three spot crabs (Ryan 1967; Sarada, 1998), however in southern Queensland, Campbell and Fielder (1986) reported that no ovigerous females were caught from May to July indicating that although three spots were capable of year-round spawning they were limited by water temperature. A similar trend has also been reported in Indian populations of three spot crabs during the monsoon season with the authors suggesting that low in-shore salinity levels may be responsible for reduced reproductive activity (Sukumaran and Neelakantan, 1998). The peak breeding season of three spot crabs in Queensland, in which over 50% of females are ovigerous, extends from October to February (Campbell and Fielder, 1986). Three spot crabs have a size-dependent fecundity ranging from 44,000 to 1.2 million eggs (Sukumaran and Neelakantan, 1997b). Sukumaran and Neelakantan (1997b) investigated the reproductive potential of the Indian population off the Karnataka coast and indicated that crabs ranging in carapace width between 100 and 120 mm contributed over 50% of the total egg production of the population.

The population dynamics of three spot crabs have been studied extensively in Indian waters (Sukumaran and Neelakantan, 1996; Sukumaran and Neelakantan, 1997; Sarada, 1998). Three spot crabs grow rapidly in their first year with a mean monthly growth rate of 10.3 and 8.8 mm and attaining carapace widths of 124.1 and 112.5 mm in males and females respectively after one year (Sukumaran and Neelakantan, 1997). In contrast Sarada (1998) indicated a faster growth rate with female three spot crabs reaching 131.5, 155.5 and 160.5 mm, and males reaching 136.8, 164.8 and 171.1 mm in their first, second and third years, respectively. Estimates of the von Bertalanffy growth parameters L_∞ (CW), K (annual) and t_0 (annual) for male and females three spot crabs by Sarada (1998) were 172.9 mm, 1.4939 and –0.0482 in males, and 161.8 mm, 1.574 and –0.0635 in females. The respective values published by Sukumaran and Neelakantan (1997) were 195 mm, 0.99, –0.0132 for males, and 188 mm, 0.82 and –0.0975 for females.

12.1.4 Mantis shrimps (Stomatopoda)

Mantis shrimps are marine crustaceans that belong to the order Stomatopoda. Historically the Australian stomatopod fauna has received very little attention with most reports detailing taxonomic and distributional details of a few species. However, Ahyong (2001) recently reviewed the Australian stomatopod fauna in which 72 species are newly reported to Australia. Currently the Australian stomatopod fauna consists of 146 species in 63 genera many of these species are widely distributed (i.e., Indo-West Pacific). Within Queensland waters there are 99 species of mantis shrimps that range in size from 19 mm to 335 mm. Furthermore, 22 of these species are endemic to Australia.

Mantis shrimps are highly specialised predators of crustaceans (mainly prawns and other mantis shrimps), and small fish (Ruppert and Barnes, 1994, Sreelatha and John, 1996). The second pair of thoracic appendages are enlarged for raptorial feeding with the inner edge of the dactyl possessing numerous long spines or shaped like the blade of a knife. Prey is captured by “spearing” or “smashing”, depending on whether the dactyl is extended or folded during the strike (Caldwell and Dingle, 1976). Mantis shrimps inhabit rock or coral crevices or in burrows excavated in the sea floor and rigorously defend their territories. They either hunt at the entrance of their burrows, crawl on the bottom or swim through the water column in search of prey. When prey is detected the raptorial claw extends with such force and speed (within four milliseconds) that captive animals have been known to break the glass of their aquariums (Jones and Morgan, 1994; Ruppert and Barnes, 1994).

Mantis shrimps are exploited in several parts of the world with the most extensive fisheries being for *Squilla mantis* in the Mediterranean, *Oratosquilla oratoria* in Japan and *Oratosquilla nepa* in India (James and Thirumilu, 1993; Ahyong, 2001). Within these markets they are used as a dependable source of raw material for fishmeal, poultry feeds, and fertilisers and are also eaten as the meat is reported to posses medicinal value (James and Thirumilu, 1993). Within Queensland, Moreton Bay appears to be where the majority of mantis shrimps are harvested. There are currently 20 species known to inhabit Moreton Bay, however some species are too small to be caught and/or inhabit un-trawlable habitats. Dell and Sumpton (1999) identified eight species of mantis shrimps within the bycatch from prawn trawling in Moreton Bay, these included *Anchisquilla fasciata, Belosquila laevis, Clorida granti, Eurosquilla woodmasoni, Harpiosquilla harpax, Odontodactylus cultrifer, Oratosquillina interrupta*, and *Oratosquillina stephensoni*. The species of mantis shrimps that grow over 100 mm (animals smaller than this are too small to market) in Queensland waters are detailed in Table 12.1.3.

The life cycle of the mantis shrimp involves four major phases: egg, larvae, juvenile and adult. Some mantis shrimp pair for life, sharing the same burrow or retreat (Rupert and Barnes, 1994). Many populations of mantis shrimps breed for extended periods often with peaks in frequency in tropical waters. For example, *Oratosquilla nepa* spawn over 10 months with peaks in February to April and September to October off the Mangalore coast (Reddy and Shanbhogue, 1994). Similarly, *Harpiosquilla melanoura* spawns over nine months from November through to June off the south-east coast of India (Lyla et al., 1999). Captive breeding studies have highlighted that mantis shrimps are capable of multiple broods. For example, *Gonodactylus bredini* can spawn up to five clutches within one year. Furthermore, Hamano and Matsuura (1984) demonstrated that a second spawning occurred 40 days after the first spawning.

Mantis shrimps usually spawn, brood and hatch their eggs within their burrows. The eggs of mantis shrimps are agglutinated to form a globular mass in which the female usually cares for and shapes during incubation (Hamano and Matsuura 1984; Morgan and Goy, 1987). The incubation period is temperature dependent and becomes shorter at higher temperatures (i.e. 8 days at 27^{o}C and 23 days at 19^{o}C in *Oratosquilla oratoria*, Hamano and Matsuura, 1987). Similarly, Morgan and Goy (1987) reported that the incubation period of *Gonodactylus bredini* required 14–15 days at 28^{o}C. Once hatched the larvae remain in the burrows and pass through one to three pelagic stages, which contain yolk and do not feed, before leaving the burrow and entering the plankton as feeding pelagic larvae. The duration and number of larval stages differs with species but ranges from eight stages over 35–50 days in *Gonodactylus bredini* (Morgan and Goy, 1987), eleven stages over 36–59 days in *Oratosquilla oratoria* (Hamano and Matsuura, 1987), and three stages over 60–70 days in *Heterosquilla tricarinata* (Greenwood and Williams, 1984). The duration of larval development is also temperature dependent (Hamano and Matsuura, 1987).

Table 12.1.3. List of the maximum size, depth range and distribution of Queensland mantis shrimp species that attain sizes greater than or equal to 100 mm in total length

Species	TL (mm)	Depth (m)	Distribution within Queensland
Anchisquilla fasciata *	100	7-55	Moreton Bay north
Anchisquilloides mcneilli	110	14-308	Coral Sea (17 deg) south
Bathysquilla crassispinosa	297	170-420	Coral Sea (23 deg) north
Bathysquilla microps	221	728-1006	Coral Sea (17 deg south)
Belosquilla laevis *	127	0-40	Mackay south
Carinosquilla australiensis	123	20-30	Princess Charlotte Bay to Keeper Reef
Carinosquilla redacta	150	20-45	Princess Charlotte Bay to Gulf of Carpentaria
Carinosquilla thailandensis	152	11-51	Shelburne Bay to Gulf of Carpentaria
Clorida bombayensis	100	0-47	Gulf of Carpentaria
Clorida wassenbergi	105	21-30	The Gulf of Carpentaria and Arafura Sea
Cloridina moluccensis	108	26-90	Gulf of Carpentaria
Cloridopsis terrareginensis	103	0-25	Carins north
Dictyosquilla tuberculata	124	5-57	Townsville to Gulf of Carpentaria
Erugosquilla grahami	177	?-66	Gulf of Carpentaria
Erugosquilla woodmasoni *	153	0-55	All QLD
Faughnia serenei	143	73-310	Coral Sea (17-22 deg)
Gonodactylus chiragra	102	Subtidal	Rockhampton to Torres Strait
Gonodactylus platysoma	110	Subtidal	Southern border to Torres Strait
Harpiosquilla annandalei	137	15-206	Gulf of Carpentaria
Harpiosquilla harpax *	262	0-93	All QLD
Harpiosquilla melanoura	168	60-80	All QLD
Harpiosquilla stephensoni	315	0-46	Yeppoon north
Kempina Mikado	182	30-804	All QLD
Lysiosquilla colemani	170	36-280	Calounda South
Lysiosquilla suthersi	195	55	Cairns (1 only)
Lysiosquilla tredecimdentata	276	Subtidal	Townsville South
Lysiosquillina maculate	335	Subtidal	All QLD
Lysiosquillina sulcata	153	6	One Tree Island (1 only)
Lysiosquilloides siamensis	180	?	Gulf of Carpentaria
Miyakea nepa	166	2-25	Hinchinbrook Island to Gulf of Carpentaria
Odontodactylus cultrifer *	125	7-51	All QLD
Odontodactylus japonicus	175	30-82	Southern border to Heron Island
Odontodactylus scyllarus	171	0-30	All QLD
Oratosquillina gravieri	123	2-59	Moreton Bay north
Oratosquillina inornata	112	Subtidal	Carins to Gulf of Carpentaria
Oratosquillina interrupta *	160	0-25	All QLD
Oratosquillina quinquedentata	155	0-51	Mackay to Gulf of Carpentaria
Oratosquillina stephensoni *	157	6-43	Moreton Bay north
Quollastria capricornae	110	71-212	All QLD
Quollastria gonypetes	104	13-73	All QLD
Quollastria kapala	110	131-411	Mooloolaba south

* indicates species, which are known to be harvested in Moreton Bay

Once the larva has metamorphosed into a juvenile it enters a growth phase. There are only a few studies that report on the population dynamics of mantis shrimps. Dell and Sumpton (1999) showed that the most abundant species of mantis shrimp in Moreton Bay, *Oratosquillina stephensoni*, exhibited bi-modal length-frequency distributions, suggesting the presence of two age cohorts and that this species exhibited fast growth (L_∞ = 163mm, K = 1.52 year^{-1}) and a high instantaneous mortality rate (3.8–4.7 year^{-1}) with an estimated life span of 2.5 years.

*12.1.5 Cuttlefish (*Sepia *spp.)*

There are at least 31 species of cuttlefish (*Sepia* spp.) in Australian waters and 17 of these are known to inhabit Queensland’s east coast (Reid, 2000; Lu, 1998). Some of these species are small and do not contribute to commercial catches while other species such as *Sepia apana* can grow up to over 50 cm in mantle length and weigh over 5 kg. The taxonomy and biology of the cuttlefish are not well understood and have received scant attention. The known distributions, depth ranges and maximum sizes of Queensland *Sepia* species are listed in Table 12.1.4.

Table 12.1.4. Distributions, depth ranges and maximum sizes of Queensland cuttlefish species

Species	Max Size DML (mm)	Depth (m)	Distribution
S. apama	520	1-100	Southern Australia: South of Moreton Bay (27^{o}25'S, 153^{o}20'E)
S. bidhaia	47	200-304	Eastern Australia : 17^{o}20'S, 146^{o}41'E to 22^{o}07'S, 153$_o$19'E
S. braggi	80	30-146	Southern Australia: South of the Gold Coast (26^{o}30'S, 153^{o}44'E)
S. cultrata	93	132-803	Southern Australia: South of the Gold Coast (26^{o}35'S, 153^{o}45'E)
S. elliptica	173	16-142	Indo-West Pacific: North of the Capricorn Group (23^{o}30'S, 152^{o}00'E)
S. latimanus	138	?	Indo-West Pacific: North of the Capricorn Group (23^{o}00'S, 152^{o}00'E)
S. limata	42	43-146	South East Australia: South of the Gold Coast (26^{o}36'S, 153^{o}35'E)
S. mestus	67	0-146	Eastern Australia: South of Lizard Island (14^{o}40'S, 145^{o}28'E)
S. mira	55	?	Eastern Australia : South of Lizard Island (14^{o}40'S, 145^{o}28'E)
S. opipara	116	83-184	Northern Australia: North of the Gold Coast (36^{o}57'S, 151^{o}45'E)
S. papuensis	99	17-155	Indo-West Pacific: All of Qld
S. pharaonis	247	25-102	Northern Australia: North of the Capricorn Group (23^{o}32'S, 151^{o}44'E)
S. plangon	88	1-83	Eastern Australia : All of Qld
S. rex	113	55-400	Southern Australia: South of the Gold Coast (22^{o}35'S, 153^{o}46'E)
S. rosella	141	27-183	South East Australia: South of the Gold Coast (27^{o}42'S, 153^{o}32'E)
S. smithi	133	33-138	Northern Australia: North of Moreton Bay (27^{o}25'S, 153o20'E)
S. whitleyana	174	23-160	Eastern Australia : All of Qld

Cuttlefish are primarily demersal ranging from shallow waters to the upper continental slope (about 600 m). Many cuttlefish species bury themselves in the sediment with only their eyes exposed. In this way they can hide from predators and ambush prey such as fish, prawns and crabs. Cuttlefish exhibit fast growth rates and typically live for 1 to 2 years. The eggs are usually large, up to the size of a ping-pong ball for *Sepia latimanus*, which places eggs individually into spaces in staghorn corals (Norman and Reid, 2000). Other *Sepia* species attach their eggs in clusters to various substrates with egg clusters of some species being removed by trawling (Boletzky, 1983; Moltschaniwskyj and Jackson, 2000). Eggs hatch as juveniles and commence feeding immediately with reproductive activity increasing in the later 1/2 to 2/3 of the life cycle (Boletzky 1983; Gabr et al., 1998). Males typically mature at much smaller sizes than females however specific information on the majority of Queensland species is currently lacking. Generally adults usually die after spawning and spawn only once, however some species of *Sepia* spawn smaller clutches of eggs over a spawning period until the ovary is empty (Boletzky, 1983; Gabr et al., 1998). Of the species encountered in Queensland only two have been studied in detail, *Sepia pharonis* and *Sepia elliptica* (Silas et al., 1985; Gabr et al., 1998; Gabr et al., 1999; Martinez and Moltschaniskyj, 1999; Martinez et al., 2000).

Sepia pharonis

Gabr et al. (1998) studied the maturation, fecundity and seasonality of reproduction of *S. pharonis* in the Suez Canal. Their study highlighted that *S. pharonis* reached sexual maturity at 61 and 122 mm mantle length (ML) for males and females, respectively, with animals migrating to breeding grounds and spawning from March to June. In contrast, Silas et al. (1985) estimated size at first maturity at 119 and 120 mm ML (male and female, respectively) with spawning occurring from October to August off the Indian coast at Madras. Maturation of both sexes of *S. pharonis* over a large size range points to considerable individual variation in size at maturity. *S. pharonis* has a maximum fecundity of 517–1525 ova for females 110–240 mm ML. Gabr et al. (1998) reported that egg clusters of *S. pharonis* were laid on hard substrates and frequently found from April to August in sheltered areas ranging from 0.5 to 5.0 m deep. In contrast with many other cephalopods *S. pharonis* appears to display a multiple spawning pattern in which it is plausible that females lay eggs in different bouts over a sizeable portion of their life cycle. The absence of dead and spent females and the highly variable ova sizes in mature animals provides additional information for the potential of continued egg production in *S. pharonis*. Furthermore, it appears that both males and females continue to feed as maturity is reached, which provides energy for oocyte production without metabolising reserves from other tissues (Gabr et al., 1999). Growth studies on *S. pharonis* show that the growth rate is different between sexes (Silas et al., 1985 Table 12.1.5)

Table 12.1.5. Age and growth increments of *S. pharonis and S. elliptica*

Age (months)	***S. pharonis*** **Male (mm)**	***S. pharonis*** **Female (mm)**	***S. elliptica*** **Sexes combined (mm)**
6	109.4	119.9	60.9
12	186.1	197.8	95.9
18	239.7	248.3	120.3
24	277.3	281.2	137.8
30	303.6	302.5	148.4
36	322	316.3	

Sepia elliptica

Silas et al. (1985) reported that *S. elliptica* reach sexual maturity between 75 and 115 mm and that spawning animals were caught between October and December, however the presence of mature animals over a prolonged period in their study suggested that breeding activity extended over a long period in a year. Although the spawning season of *S. elliptica* is yet to be determined in Queensland waters, Moltschaniwskyj and Jackson (2000) obtained egg clusters of *S. elliptica* from trawling in July for captive juvenile growth studies. Furthermore, Martinez and Moltschaniwskyj (1999) collected adults from February to November and the eggs laid by these captive broodstock were used for juvenile growth studies. This indicates that *S. elliptica* has a prolonged spawning season in Northern Queensland. Kasim (1993) reported on the population dynamic of *Sepia elliptica* and that the von Bertalanffy growth parameters, L_{∞}, K and t_0 to be 174 mm, 0.0887 and –0.7478 respectively.

12.1.6 Octopus (Octopus *spp.)*

The taxonomy of benthic octopuses (family Octopododa) is very poor with several Queensland species being undescribed or poorly described (Norman, 1998). As a consequence very little is known about Queensland's octopuses with almost all published information detailing taxonomic descriptions and biogeographic data. A taxonomic key of some of the better known octopus occurring in the central and western Pacific has been compiled by Norman (1998).

Although species-specific information on the biology, distribution and importance to fisheries in currently lacking for the majority of Queensland's octopus fauna, there are several general characteristics of the biology and ecology of octopus. Octopuses belonging to the Octopodidae family are bottom-dwelling species inhabiting intertidal areas through to 5 km deep. They inhabit a wide range of habitats ranging from soft substrates to coral reefs and generally are more active at night foraging for crabs, shellfish and fish. All octopuses have short life cycles (typically 1–2 years) in which growth is relatively fast (Wells and Wells, 1977; Joll, 1983; Van Heukelum, 1983). Females produce a single egg mass, lay their eggs in crevices or lairs, protect and clean the eggs during incubation and die when the eggs have hatched (Wells and Wells 1977; Norman and Reid, 2000). Fertilisation takes place within the oviduct or ovary in which the male inserts a specialised arm holding the spermatophores into the mantle of the female (Wells and Wells 1977). Octopus produce either small numbers of large eggs, in which the young hatch as benthic juveniles, or large numbers of small eggs in which the young hatch as pelagic larvae.

Many of the Queensland octopus species do not inhabit trawlable habitats and do not contribute to the QECTF. Information from recent research surveys, Norman and Reid (2000) and Norman (1998), indicate that the most likely species to be caught in commercial quantities by trawling on the east coast of Queensland are *Octopus australis, Octopus dierythraeus*, *Octopus exannulatus*, *Octopus graptus, Octopus marginatus* and the eye-cross octopus (*Octopus* cf *kagoshimensis*). Details of these octopus distributions and known biological details are given in Table 12.1.6.

Table 12.1.6. Distributions, depth ranges and known biological information of commercially important octopuses from Queensland waters

SPECIES	Distribution in Qld	Depth (m)	Maximum Size TL and weight	Egg length	Largest known fecundity
O. australis[1]	South of 25 °S	3-134	282 mm **?** g	12mm	Unknown
O. dierythraeus[2]	North of 21°S	0-78	810 mm 1500 g	14 mm*	350
O. exannulatus[3]	North of 27°S	0-84	200 mm 75 g	3.9mm	5000
O. graptus[2]	North of 19°S	11-36	1300 mm 4200 g	28 mm	680
O. marginatus[4]	North of 27°S	1-190m	300 mm 400 g	3 mm	100,000
O. cf *kagoshimensis*[5]	South of 23 °S	1-115	335 mm 200 g	3.8 mm	60,000

[1] Stranks and Norman 1992; [2] Norman 1992a; [3] Norman 1992b; **4** Norman 1998*; [5] Norman unpublished data. * measurement from a sub-mature animal.

*12.1.7 Pipehorses (*Solegnathus *spp.)*

Pipehorses are unusual fish belonging to the family Syngnathidae, which also includes the pipefish, seadragons and seahorses. Over-exploitation of some *Syngnathids* species has resulted in the family being red listed as vulnerable under the International Union for Conservation. Currently there are two species of pipehorses that are retained by commercial fishers, *Solegnathus hardwickii* and *Solegnathus dunckeri*. Both species are endemic to Australia and are among the largest species of syngnathids in the world. As a result they are highly valuable in the Asian medicine market and can obtain prices varying from \$130 to \$1300 kg^{-1}. Currently Queensland exports between 800–1000 kg of dried pipehorses per year (Connolly et al., 2001). Anecdotal evidence from fishers indicates that each pipehorse averages \$10 per fish, therefore, as 7067 pipehorses were recorded in logbook data in 2000 the approximate value of the fishery is \$70,000.

Despite their large size and economic importance very little is known about the biology and ecology of *Solegnathus* species. *S. hardwickii* is distributed from Cairns (16°55’ S) to south of the Tweed River (28°10’ S) whereas *S. dunkeri* is distributed from Fraser Island south to Booti Booti (36°16’ S) (Pogonoski et al., 2001). Current information on the habitat and depth distribution is limited as observations are based solely from trawl captures. Connolly et al., (2001) reported that pipehorses were only caught at depths greater than 25 m and appeared to be more abundant with proximity to reefs in areas having some three-dimensional structure such as sponges and gorgonian corals. A closely related species from southern Australia, *S. spinossimus*, has been recorded from 300-400 m with divers observing them living around sea whips (Edgar, 1997). The extent of movement by *S. hardwickii* and *S. dunckeri* is unknown, but they are likely to be sedentary as they lack a caudal fin and have prehensile tails.

Syngnathids are unusual fish in that the male incubates the eggs. Male *Solegnathus* species have their eggs embedded in a spongy brood patch on the ventral surface of the tail. Other species of large syngnathids from Australian waters that use this mode of reproduction include the seadragons *Phyllopteryx taeniolatus* and *Phycodurus eques* (Mackay, 1998). Pregnant males of *S. hardwickii* have been found from July through to October (QFS, 2001). In contrast, Connolly et al. (2001) reports that pipehorses breed year round with a peak in reproductive activity from mid-winter to spring based on the observation of the presence of egg scars. However, it must be noted that the duration and persistence of egg scars on *Solegnathus* species is currently unknown. The minimum size at maturity for male *S. hardwickii* is 322 mm and the size at which 50% of pipehorses are mature is 420 mm (Connolly et al., 2001). Although the brood duration is not known for pipehorses, the seadragons *Phyllopteryx taeniolatus* and *Phycodurus eques,* which display a similar reproductive strategy, incubate their eggs for 4–5 weeks and eggs hatch over 10 days (Groves, 1998). This strategy is believed to distribute the young over a wider area, offering the young less competition from siblings. Brood size in *S. hardwickii* ranges from 19–207 with eggs measuring 5 mm in diameter. At hatching juveniles measure 34 mm in total length and for the first nine months they grow at 1.2 mm per day, however this growth rate slows down to 0.3–0.5 mm per day once pipehorses are approaching adult sizes. Current estimates of longevity in *S. hardwickii* indicate that pipehorses live for 3–5 years and reach a maximum size of 515 mm.

*12.1.8 Pinkies (*Nemipterus *spp.)*

Fishes belonging to the Nemipteridae family are marine perciformes that occur in the tropical–subtropical Indo-West Pacific region and inhabit mud and sand bottoms to a depth of 410 m, although most species occur in much shallower waters. They belong to the superfamily Sparoidea, a monophyletic group that also include members of the families Sparidae (porgies), Lethrinidae (emperor fishes and large eye breams), Centracanthidae (Picarels) and Lutjanidae (snappers) (Russell, 1990). The genus *Nemipterus* is one of five genera belonging to the Nemipteridae family. *Nemipterus* fishes are typically pink with yellow, red and/or blue markings with a slender to ovate body shape. There are currently seven species of *Nemipterus* that are distributed along Queensland’s east coast. However, the catch composition and biology of these species caught by trawlers in Australian waters are poorly understood. *N. aurifilum* (yellowlip butterfly bream) and *N. theodorei* (Theodore’s butterfly bream) inhabit depths ranging from 24–220 m and 19–410 m, respectively, and are endemic to the east coast of Australia. *N. furcusus* (rosy threadfin bream), *N. hexodon* (yellow banded butterfly bream) and *N. peronii* (notched threadfin bream) have wider distributions being also found throughout South-East Asia and inhabit depths down to 110 m, 80 m and 100 m, respectively (Russell, 1990). Two other species *N. marginatus* (no local common name, to 70 m) and *N. nematopus* (yellow-tipped threadfin bream, to 102 m) have been caught on the eastern tip of Cape York.

Several studies have investigated the reproductive biology of a variety of *Nemipterus* species and indicate that fish mature and spawn after one year (Eggleston, 1972; Sainsbury and Whitelaw 1984; Acharya, 1990; Samuel, 1990; Vivekanandan, 1991). The maturity stage of the testes is difficult to assess by eye as its appearance changes little throughout the year and are relatively small in mature fish (i.e. 1/7 of the body cavity length, Eggleston, 1972). Ovarian development is easily divided into various stages of development through macroscopic examination. In young fish the ovary develops from a small thread to a short solid cylinder and in contrast to the testis lies beneath the peritoneum. During vitellogenesis the ovary grows to approximately 1/3 to 1/2 of the body cavity length with opaque oocytes clearly visible to the naked eye. In fully mature fish the ovary is blotched with clusters of hydrated eggs and vitellogenic eggs of a range of sizes. As no wholly ripe gonads have been found and vitellogenic eggs are present over a prolonged period in *Nemipterus* species, they are most likely to be fractional spawners releasing eggs at several spawnings throughout the breeding season (Eggleston, 1972). This mode of reproduction is the dominant mode displayed by tropical and warm temperate marine fishes (Pankhurst, 1998), and within the closely related Sparidae family daily broadcast spawning at dusk is common (Haddy and Pankhurst, 1998; Scott et al., 1993). However, the spawning behaviour and periodicity and timing of spawning in *Nemipterus* species is currently unknown. The fecundity of Nemipterids is directly related to the size of the fish (Eggleston, 1972; Murty, 1984; Mohan and Velayudhan, 1986; Raje, 1996). Fecundity estimates range from 5344 to 64,369 eggs in *N. mesoprion* (Raje, 1996); 23,049 to 139,160 eggs in *N. japonicus* (Murty, 1984), and 86,184 to 497,230 eggs in *N. delagoae* (Mohan and Velayudhan, 1986). The eggs of *N. virgatus* are small (0.7–0.8 mm), colourless, buoyant and spherical and hatch in 24 hours as yolk sac larvae measuring 1.7 mm in length (Aoyama and Sotogaki, 1955; Renzhai and Suifen, 1980).

Nemipterid fishes are entirely carnivorous fishes that feed by sight during the day. Their main prey items are crustaceans (60–75%), but they also consume small fish, (8–30%), polychaetes (3–6%) and cephalopods (0.4–5%) (Eggleston 1972; Sainsbury and Whitelaw, 1984; Salini et al., 1994). Many *Nemipterus* species show size-related differences in sex ratio, with large specimens being mainly males. This size-related skew in sex ratios appears to be due to faster growth rates in males as growth slows at the onset of sexual maturity in females (Eggleston, 1972; Russell, 1990; Samuel, 1990), however, there is evidence of protogynous hermaphroditism in *N. furcosus* (Young and Martin, 1985). Other species of *Nemipterus* appear to be non-functional rudimentary hermaphrodites in which males have functional testies, but retain rudimentary ovarian tissue throughout their life (Young and Martin, 1985; Lau and Sadovy, 2001).

The von Bertalanffy growth parameters have been estimated for several species of *Nemipterus,* however, most of these studies have concentrated on populations from Asian waters (India to Hong Kong) where substantial fisheries exist for these species. The mean population parameter estimates generated for *N. furcosus, N. hexodon N. marginatus* and *N. peronii* in these studies are summarised in Table 12.1.7. Values of K and L_∞ reported for *Nemipterus* by Pauly (1980) range from 0.27–0.98 and 19.5–31.5, respectively. *N. furcosus* and *N. peronii* are the only species in which the von Bertalanffy growth parameters have been determined in Australian waters. Sainsbury and Whitelaw (1984) collected otoliths from *N. furcosus* captured at the North-West Shelf (WA) and estimated L_∞, K, t_o and M to be 41.9 cm, 0.25, 0.74 years and 1.85 respectively, however these findings were outside the previously known ranges of the genus indicated by Pauly (1980). Morales-Nin (1989) used several methods to estimate the growth parameters of *N. furcosus* from the North-West Shelf and reported values of L_∞ and K ranging from 26.7–28.4 cm and 0.42–0.71, respectively.

Table 12.1.7. Population parameter estimates for Queensland Nemipterid species. Note: Parameter estimates were derived from Fishbase 99 using the references cited below.

Species	L_∞	K	t_0	M **at 25°C**	**Life span** (yrs)	t_m (yrs)	L_m (TL)
N. aurifilum[1]	18.5 (SL)	?	?	?	?	?	?
N. furcosus[2]	26.7 (TL)	0.45	-0.38	0.94	6.3	1.7	16.0
N. hexodon[3]	25.5 (TL)	0.48	-0.36	1.00	5.9	1.5	15.3
N. marginatus[4]	19.5 (TL)	0.63	-0.29	1.2	4.5	1.2	12.0
N. nematopus[1]	18.5 (SL)	?	?	?	?	?	?
N. peronii[5]	28.5 (TL)	0.44	-0.38	0.91	6.4	1.7	16.9
N. theodorei[1]	20.0 (SL)	?	?	?	?	?	?

[1] Russell 1990; [2] Morales-Nin 1989; [3] Tandog-Edralin, et al. 1988;. Dwiponggo, et al. 1986; Pauly 1980; [4] Weber & Jothy 1977; [5] Ingles & Pauly 1984; Weber & Jothy 1977;. Wu & Yeh 1986.

12.2 REFERENCES

Acharya, P., 1990. Studies on maturity, spawning and fecundity of *Nemipterus japonicus* (Bloch) off Bombay Coast. J. India Fish. Assoc. 20, 51-57.

Ahyong, S.T., 2001. Revision of the Australian stomatopod crustacea. Records of the Australian Museum, Supplement 26: 1-326.

Aoyama, T.,Sotogaki, N., 1955. On the development of the egg of *Nemipterus virgatus* (Houttuyn). Jap. J. Ichthyol. 4, 130-132.

Atkinson, J.M.,Boustead, N.C., 1982. The complete larval development of the scyllarid lobster *Ibacus alticrenatus* Bate, 1888 in New Zealand waters. Custaceana 42, 275-287.

Baisre, J.A., 1994. Phyllosoma larvae and the phylogeny of palinuroidea (Crustacea: Decapoda): a review. Aust. J. Mar. Freshwat. Res., 45, 925-944.

Bishop, G.A.,Williams, A.B., 1986. The fossil lobster *Linuparus canadensis* , Carlile Shale (Cretaceous), Black Hills. Natl. Geogr. Res., 2, 372-387.

Boletzky, S.V., 1983. *Sepia officnalis*. In: P.R. Boyle, Cephalopod Life Cycles Volume 1, Species Accounts. Academic Press, New York, pp 267-276.

Brown, D.E., Hothuis, L.B., 2000. The Australian species of the genus *Ibacus* (Crustacea: Decapoda: Scyllaridae), with the description of a new species and addition of new records. Zool. Med. Leiden, 72, 113-141.

Caldwell, R.L., Dingle, H., 1976. Stomatopods. Sci. Am., 234; 80-89.

Campbell, G.R., Fielder, D.R., 1986. Size at sexual maturity and occurrence of ovigerous females in three species of commercially exploited portunid crabs in S.E. Queensland. Proc. R. Soc. Qld. 97, 79-87.

Chaplin, J., Yap, E.S., Sezmis, E., Potter, I. C., 2001. Genetic (microsatellite) determination of the stock structure of blue swimmer crab in Australia. Fisheries Research & Development Corporation, Final Report 1998/118. pp. 84.

Connolly, R.M., Cronin, E.R., Thomas, B.E., 2001. Trawl bycatch of sygnathids in Queensland: catch rates, distribution and population biology of *Solegnathus* pipehorses (seadragons). Fisheries Research & Development Corporation Final Report 1999/124. pp 57.

Dell, Q., Sumpton, W. 1999. Stomatopod by-catch from prawn trawling in Moreton Bay, Australia. Asian Fish. Sci., 12, 133-144.

Dwiponggo, A., Hariati, T., Banon, S., Palomares M.L., Pauly D., 1986. Growth, mortality and recruitment of commercially important fishes and penaeid shrimps in Indonesian waters. ICLARM Tech. Rep. 17, 91 p.

Edgar, G.J., 1997. Australian Marine Life: The plants and animals of temperate waters. Reed Books, Australia. P. 425.

Eggleston, D., 1972. Patterns of biology in the nemipteridae. J. Mar. Biol. Ass. India, 14, 357-364.

Gabr, H.R., Hanlon, R.T., Hanafy, M.H., El-Etreby, S.G., 1998. Maturation, fecundity and seasonality of reproduction of two commercially valuable cuttlefish, *Sepia pharonis* and *S. dollfusi,* in the Suez Canal. Fish. Res. 36, 99-115.

Gabr, H.R., Hanlon, R.T., El-Etreby S.G. & Hanafy, M.H., 1999. Reproductive versus somatic tissue growth during the life cycle of the cuttlefish *Sepia pharonis* Ehrenberg, 1831. Fish. Bull. 97, 802-811.

Greenwood, J.G., Williams, B.G., 1984. Larval and early post-larval stages in the abbreviated development of *Heterosquilla tricarinata* (Claus, 1871) (Crustacea, Stomatopoda). J. Plankton. Res., 6, 615-635.

Groves, P., 1998. Leafy Sea Dragons. Sci. Am. December, pp 54-59.

Haddy, J.A., Pankhurst, N.W., 1998. Annual change in reproductive condition and plasma concentrations of sex steroids in black bream, *Acanthopagrus butcheri* (Munro) (Sparidae). Mar. Freshwat. Res. 49, 389-397.

Hamano, T., Matsuura, S., 1984. Egg laying and egg mass nursing behaviour in the Japanese mantis shrimp. Bull. Jap. Soc. Sci. Fish., 50, 1969-1973.

Hamano, T., Matsuura, S., 1987. Egg size, duration of incubation and larval development of the Japanese mantis shrimp in the laboratory. Nip. Sui. Gak. 53, 23-39.

Holthuis L.B., 1991. FAO species catalogue; Vol 13. Marine lobsters of the world. An annotated and illustrated catalogue of the species of interest to fisheries known to date. FAO Fish. Synops. 13(125):292 p.

Ingles, J., Pauly, D., 1984. An atlas of the growth, mortality and recruitment of Philippines fishes. International Centre for Living Aquatic Resources Management, Manila, Philippines. ICLARM Tech. Rep. 13. 127 p.

James, D.B., Thirumilu, P., 1993. Population dynamics of *Oratosquilla nepa* in the trawling grounds off Madras. J. Mar. Biol. Ass. India. 35. 135-140.

Kasim, H.M., 1993. Population dynamics of the cuttlefish *Sepia elliptica* Hoyle in Saurashtra waters. J. Mar. Biol. Ass. India, 35, 80-86.

Kim, C.-H., 1977. Gametogenesis and early development of *Linuparus trigonus* (von Siebold) Bull. Korean Fish. Soc. 10, 71-96.

Joll, L.M., 1983. *Octopus tetricus.* In: P.R. Boyle, Cephalopod Life Cycles Volume 1, Species Accounts. Academic Press, New York, pp 267-276.

Lau, P.P., Sadovy, Y., 2001. Gonad structure and sexual pattern in two threadfin breams and possible function of the dorsal accessory duct. J. Fish Biol. 58, 1438-1453.

Lipcius, R.N., Cobb, J.S., 1994. Introduction; Ecology and fishery biology of spiny lobsters. In: Phillips, B.F., Cobb J.S., Kittaka, J. (eds), Spiny Lobster Management. Blackwell Scientific, Australia. pp 1-24.

Lu, C.C., 1988. A synopsis of Sepiidae in Australian waters (Cephalopoda: Sepioidea). In: Voss, N.A., Vecchione, M., Toll, R.B., Sweeney M.J. (eds), Systematics and Biogeography of Cephalopods. Smithsonian Contributions to Zoology, 586, 159-190.

Lyla, P.S., Panchatcharam, K., Ajmal Khan, S., 1999. Breeding biology of the stomatopod *Harpiosquilla melanoura* (Crustacea: Stomatopoda) occurring in Parangipettai waters, south-east coast of India. Indian J. Mar. Sci. 28, 87-88.

Mackay, B. 1998. Seadragons in wild and captive environments. Todays Aquarist 7, pp 5-9.

Martinez, P., Bettencourt, V., Guerra, A., Moltschaniwskyj, N.A., 2000. How temperature influences muscle and cuttlebone growth in juvenile cuttlefish (*Sepia elliptica*) (Mollusca: Cephalopoda) under conditions of food stress. Can. J. Zool. 78, 1855-1861.

Martinez, P., Moltschaniwskyj, N.A., 1999. Description of growth in the tropical cuttlefish *Sepia elliptica* using muscle tissue. J. Mar. Biol. Ass. UK. 79, 317-321.

Melville-Smith, R., Bellchambers, L.M., Kangas, M., 2001. The collection of fisheries data for the management of the blue swimmer crab fishery in central and lower west coasts of Australia. Fisheries Research & Development Corporation Final Report 1998/121. pp. 99.

Mikami, S., Takashima, F., 1993. Development of the proventriculus in larvae of the slipper lobster, *Ibacus ciliatus* (Decapoda: Scyllaridae). Aquaculture, 116, 199-217.

Moltschaniwskyj, N.A., Jackson, G.D., 2000. Growth and tissue composition as a function of feeding history in juvenile cephalopods. J. Exp. Mar. Biol. Ecol. 253, 229-241.

Morgan, S.G., Goy, J.W., 1987. Reproduction and larval development of the mantis shrimp *Gonodactylus bredini* (Custacea: Stomatopoda) maintained in the laboratory. J. Crust. Biol. 7; 595-618.

Mohan, M., Velayudhan, A.K., 1986. Spawning biology of *Nemipterus delagoae* (Smith) at Vizhinjam. J.Mar. Biol. Assoc. India. 28, 26-34.

Morales-Nin, B., 1989. Growth determination of tropical marine fishes by means of otolith interpretation and length analysis. Aquat. Living Resour. 22, 241-253.

Murty, V.S., 1984. Observations on the fisheries of threadfin breams (Nemipteridae) and on the biology of *Nemipterus japonicus* (Bloch) from Kakinada. Indian J. Fish. 31, 1-18.

Norman, M. D., 1992a. Four new octopus species of the *Octopus macropus* group (Cephalopoda: Octopodidae) from the Great Barrier Reef, Australia. Memoirs of the Museum of Victoria. 53, 267-308.

Norman, M. D., 1992b. Ocellate octopuses (Cephalopoda: Octopodidae) of the Great Barrier Reef, Australia: Descriptions of two new species and redescription of *Octopus polyzenia* Gray, 1849. Memoirs of the Museum of Victoria. 53, 309-344.

Norman, M.D., 1998. Octopodidae; Benthic octopuses. In: Carpenter, K.E., Niem, V.H. (eds), FAO species identification guide for fishery purposes. The living marine resources of the Western Central Pacific. Volume 2: FAO, Rome.

Norman, M. D., Reid, A. L., 2000. A guide to squid, cuttlefish and octopuses of Australia. CSIRO Publishing, Collingwood, pp. 95.

Pankhurst, N.W., 1998. Reproduction. In: Black, K.D., Pickering, A.D. (Eds.), Biology of Farmed Fish. Sheffield Academic Press, Sheffield. pp. 1-26.

Pauly, D., 1980 On the interrelationships between natural mortality, growth parameters and mean environmental temperature in 175 fish stocks. J. Cons. Cons. Int. Explor. Mer. 39, 175-192.

Pogonoski, J.J., Pollard, D.A., Paxton, J.R., 2001. Conservation overview and action plan for Australian threatened and potentially threatened marine and estuarine fishes. Report to Natural Heritage Division of Environment Australia.

Potter, I.C., Lestang, S.D., Melville-Smith, R., 2001. The collection of biological data required for management of the blue swimmer crab fishery in the central and lower west coasts of Australia. Fisheries Research & Development Corporation Final Report 1997/137. pp. 53.

QFS 2001, Fisheries (East Coast Trawl) Management Plan 1999; Plan Review Paper, Permitted Fish (other than principal fish) and Steaming Day Review.

Raje, S.G., 1996. Some observations on the biology of *Nemipterus mesoprin* (Bleeker) from Veraval (Gujarat). Indian J. Fish. 43, 163-170.

Reddy, H.R.V., Shanbhogue, S.L., 1994a. The reproductive biology of the mantis shrimp, *Oratosquilla nepa* (Latreille) from Mangalore. Mahasagar. 27, 67-72.

Reid, A.L., 2000. Australian cuttlefishes (Cephalopoda:Sepiidae): the doratosepion species complex. Invert. Zool. 14, 1-76.

Renzhai, Z., Suifen, L., 1980. On the eggs and larvae of the goldern-thread *Nemipterus virgatus* (Houttuyn). Acta Zool. Sin. 26, 136-139.

Ritz, D.A., Thomas, L.R., 1973. The larval and postlarval stages of *Ibacus peronii* Leach (Decapoda, Reptantia, Scyllaridae). Crustaceana. 24, 5-17.

Rupert, E.E., Barnes, R.D. 1994. Invertebrate Zoology. Saunders College Publishing, Sydney. pp. 1056.

Russell, B.C., 1990. Nemipterid fishes of the world. (Threadfin breams, whiptail breams, monocle breams, dwarf monocle breams, and coral breams). Family Nemipteridae. An annotated and illustrated catalogue of nemipterid species known to date. FAO Fish. Synops. 12(125):149 p.

Ryan, E.P., 1967. The morphometry of sexually mature instars of the crab *Portunus sanguinolentus* (Herbst) (Brachyura: Portunidae). Proc. Symp. Crust., Mar. Biol. Ass. India, Part II: 715-723.

Sainsbury, K.J., Whitelaw, W.A., 1984. Biology of Peron's threadfin bream, *Nemipterus peronii* (Valenciennes), from the north-west shelf of Australia. Aust. J. Mar. Freshwat. Res. 35, 167-185.

Salini, J.P., Blaber, J.M., Brewer, D.T., 1994. Diets of trawled predatory fish of the Gulf of Carpentaria, Australia, with particular reference to predation on prawns. Aust. J. Mar. Freshwat. Res. 45, 397-411.

Samuel, M., 1990. Biology, age, growth and population dynamics of threadfin bream *Nemipterus japonicus*. J. Mar. Biol. Assoc. India. 32, 66-76.

Sarada, P.T., 1988. Crab fishery of the Calicut coast with some aspects of the population characteristics of *Portunus sanguinolentus, P. pelagicus* and *Charybdis cruciata*. Indian J. Fish. 45, 375-386.

Scott, S.G., Zeldis, J.R., Pankhurst, N.W., 1993. Evidence of daily spawning in natural populations of the New Zealand snapper *Pagrus auratus* (Sparidae). Environ. Biol. Fish. 36, 149-56.

Silas, E.G., Sarvesan, R., Prabhakaran-Nair, K., Appanna-Sastri, Y., Sreenivasan, P.V., Meiyappan, M.M., Kuber-Vidyasagar, Satyanarayana-Rao, K., Narayana-Rao, B., 1985. Some aspects of the biology of cuttlefishes. CMFRI Bull. 37, 49-70.

Sreelatha, A. John, P.A., 1996. Food and feeding habits of *Oratosquilla nepa* (Crustacea-Stomatopoda). J. Mar. Biol. Assoc. India. 38, 114-117.

Stewart, J., Kennelly, S.J., 1997. Fecundity and egg-size of the Balmain bug *Ibacus peronii* (Leach, 1815) (Decapoda, Scyllaridae) off the east coast of Australia. Crustaceana. 70, 191-197.

Stewart, J., Kennelly, S.J., 1998. Contrasting movements of two exploited Scyllarid lobsters of the genus Ibacus off the east coast of Australia. Fish. Res. 36, 127-132.

Stewart, J., Kennelly, S.J., 2000. Growth of the scyllarid lobsters *Ibacus peronii* and *I. chacei*. Mar. Biol. 136, 921-930.

Stewart, J., Kennelly, S.J., Hoegh-Guldberg, O., 1997. Size at sexual maturity and the reproductive biology of two species of Scyllarid lobsters from New South Wales and Victoria, Australia. Crustaceana. 70, 344-367.

Stranks, T.N., Norman, M.D., 1992. Review of the *Octopus australis* complex from Australia and New Zealand, with description of a new species (Mollusca: Cephalopoda). Memoirs of the Museum of Victoria. 53, 345-373.

Sukumaran, K.K., Neelakantan, B., 1996. Relative growth and sexual maturity in the marine crabs, *Portunus (Portunus) sanguinolentus* (Herbst) and *Portunus (Portunus) pelagicus* (Linnaeus) along the south-west coast of India. Indian J. Fish. 43, 215-223.

Sukumaran, K.K., Neelakantan, B., 1997a. Food and feeding of *Portunus (Portunus) sanguinolentus* (Herbst) and *Portunus (Portunus) pelagicus* (Linnaeus) (Brachyura:Portunidae) along the Karnataka coast. Indian J. Mar. Sci. 26, 35-38.

Sukumaran, K.K., Neelakantan, B., 1997b. Sex ratio, fecundity and reproductive potential in two marine portunid crabs, *Portunus* (Portunus) *sanguinolentus* (Herbst) and *Portunus* (Portunus) *pelagicus* (Linnaeus) along the Karnataka coast. Indian J. Mar. Sci. 26, 43-48.

Sukumaran, K.K., Neelakantan, B., 1998. Maturation process and reproductive cycle in two marine crabs, *Portunus* (Portunus) *sanguinolentus* (Herbst) and *Portunus* (Portunus) *pelagicus* (Linnaeus) along the Karnataka coast. Indian J. Fish. 45, 257-264.

Sumpton, W.D., Smith, G.S., Potter, M.A., 1989. Notes on the biology of the Portunid crab *Portunus sanguinolentus* (Herbst), in subtropical Queensland Waters. Aust. J. Mar. Freshwat. Res. 40, 711-717.

Sumpton, W.D., Gaddes, S., McLennan, M., Campbell, M., Tonks, M., Good, N., Hagedoorn, W., 2002. Assessing the blue simmer crab fishery in Queensland. Fisheries Research & Development Corporation Draft Report 1998/117. pp 151.

Suthers, I.M., Anderson, D.T., 1981. Functional morphology of mouthparts and gastric mill of *Ibacus peronii* (Leach) (Palinura: Scyllaridae). Aust. J. Mar. Freshwat. Res. 32, 931-944.

Takahashi, M., Saisho, T., 1978. The complete larval development of the Scyllarid lobster, *Ibacus ciliatus* (Von Siebold) and *Ibacus novemdentatus* (Gibbes) in the laboratory. Mem. Fac. Fish. Kagoshima Univ. 27, 305-353.

Tandog-Edralin, D., Ganaden S.R., Fox, P. 1988. A comparative study of fish mortality rates in moderately and heavily fished areas of the Philippines. p. 468-481. In: Venema, S.C., Christensen J.M., Pauly D., (eds.) Contributions to tropical fisheries biology. FAO/DANIDA Follow-up Training Course on Fish Stock Assessment in the Tropics, Denmark, 1986 and Philippines, 1987. FAO Fish. Rep. (389).

Van Heukelem, W.F., 1983. *Octopus cyanea*. In: Boyle, P.R., Cephalopod Life Cycles Volume 1, Species Accounts. Academic Press, New York. pp. 267-276.

Vivekanandan, E., 1991. Spawning and growth of three species of threadfin breams off Madras. Indian J. Fish. 38, 9-12.

Ward, T.J., Unpublished Data. Diel variability in catches of the deep-water lobster *Linuparus trigonus* on the continental slope of Queensland Australia. p. 17.

Wassenberg, T.J., Hill, B.J., 1982. Diets of four decapod crustaceans (*Linuparus trigonus, Metanephrops andamanicus, M. australiensis* and *M. boschmai*) from the continental shelf around Australia. Mar. Biol. 103, 161-167.

Wassenberg, T.J., Hill, B.J., 1989. Diets of four decapod crustaceans (*Linuparus trigonus, Metanephrops andamanicus, M. australiensis* and *M. boschmai*) from the continental shelf around Australia. Mar. Biol. 103, 161-167.

Weber, W., Jothy, A.A., 1977. Observations on the fish *Nemipterus* spp. (family Nemipteridae) in the coastal waters of East Malaysia, 1972. Arch. FischWiss. 28, 109-122.

Wells, M.J., Wells, J., 1977. Cephaloda: Octopoda. In: Giese A.C., Pearse, J.S., (eds), Reproduction of Marine Invertebrates, Volume IV. Academic Press, New York, pp. 291-336.

Wu, R.S.S., Shin, P.K.S., 1998. Food segregation in three species of portunid crabs. Hydrobiologia. 362, 107-113.

Wu, C.-L., H.-C., Yeh, S.-Y., 1986. Age and growth of *Nemipterus peronii* (Cuvier) in the northwestern shelf off Australia. Acta Oceanogr. Taiwanica 16:74-89.

Young, P.C., Martin, R.B., 1985. Sex ratios and hermaphroditism in nemipterid fish from northern Australia. J. Fish. Biol. 26, 273-287.

13 The fishery and reproductive biology of barking crayfish, *Linuparus trigonus* (Von Siebold, 1824) in the Queensland East Coast Trawl Fishery.

J. A. Haddy, D. P. Roy and A. J. Courtney

13.1 ABSTRACT

This chapter describes the fishery and reproductive biology for *Linuparus trigonus* obtained from trawl fishers operating off Queensland's east coast, Australia. The smallest mature lobster measured 59.8 mm CL, however, 50% maturity was reached between 80 and 85 mm CL. Brood fecundity (BF) was size dependent and ranged between 19,287 and 100,671 eggs in 32 females from 59.8 to 104.3 mm CL. The relationship was best described by the power equation $BF = 0.1107*CL^{2.9241}$ ($r^2 = 0.74$). Egg size ranged from 0.96 to 1.12 mm in diameter (mean = 1.02 ± 0.01 mm). Egg weight and size were not related to lobster size. Length-frequency distributions displayed a multi-modal distribution. The percentage of female to male lobsters was relatively stable for small size classes (30 to 70 mm CL; 50.0 to 63.6% females), but female proportions rose markedly between 75 and 90 mm (72.2 to 85.4%) suggesting that at the onset of sexual maturity female growth rates are reduced. In size classes greater than 95 mm, males were numerically dominant. A description of the *L. trigonus* fishery in Queensland is also detailed.

13.2 INTRODUCTION

Barking crayfish, *Linuparus trigonus* (Von Siebold, 1824), also known as spear or champagne lobster, is one of three extant species of the genus *Linuparus*, which is one of eight genera of the family Palinuridae (spiny lobsters) (Holthuis, 1991). Unlike most spiny lobsters, *Linuparus* spp. are generally found in deep water (81–328 m) and restricted to the Indo-West Pacific region (Bruce, 1965; Berry and George, 1972). *Linuparus* lobsters generally occur in relatively low abundance (Holthuis, 1991), however, *L. trigonus* occurs in sufficient densities off Townsville, Australia to support a targeted commercial fishery and also contribute as an important byproduct throughout the Queensland East Coast Trawl Fishery (QECTF). However, it is currently unknown whether present exploitation levels are sustainable as very little is known about the population dynamics of *L. trigonus*.

Size at sexual maturity and fecundity are some of the most important life history parameters needed for stock assessment and management of sustainable exploitation levels (Chubb, 1994). These parameters can be used with other population parameter estimates such as growth and mortality to develop yield- and egg-per-recruit models. Discard mortality of trawl-caught crustaceans is relatively low compared to fish (Hill and Wassenberg, 1990), which enables minimum legal size limits to be effective management strategies. Currently there is no biological information on *L. trigonus* to establish a minimum legal size. The aim of this study was to describe the fishery and reproductive biology of *L. trigonus*, to assist in the development of sustainable management strategies.

13.3 MATERIALS AND METHODS

Mandatory logbook data of *L. trigonus* from 2000–2002 were used to examine the spatial distribution (30 minute grids), total catch, total effort, and catch per unit effort along the Queensland east coast. Pre-2000 data could not be used in the analyses due to taxonomic uncertainties in the lobster data associated with other spiny lobster species.

A sampling program was undertaken between October 2001 and February 2003 and was totally reliant upon commercial trawl fishers operating between Townsville and Mooloolaba (Figure 13.3.1) to donate lobsters. An additional frozen sample of ovigerous females caught in August 2000 was also provided. Lobster sample sizes ranged between 7 and 182 individuals and samples were obtained from depths between 120 m and 238 m. Because the targeted fishing effort for *L. trigonus* is intermittent throughout the year due to fishers targeting other, more valuable species, samples were not provided in November 2001 to January 2002, August to September 2002, and December 2002 to January 2003.

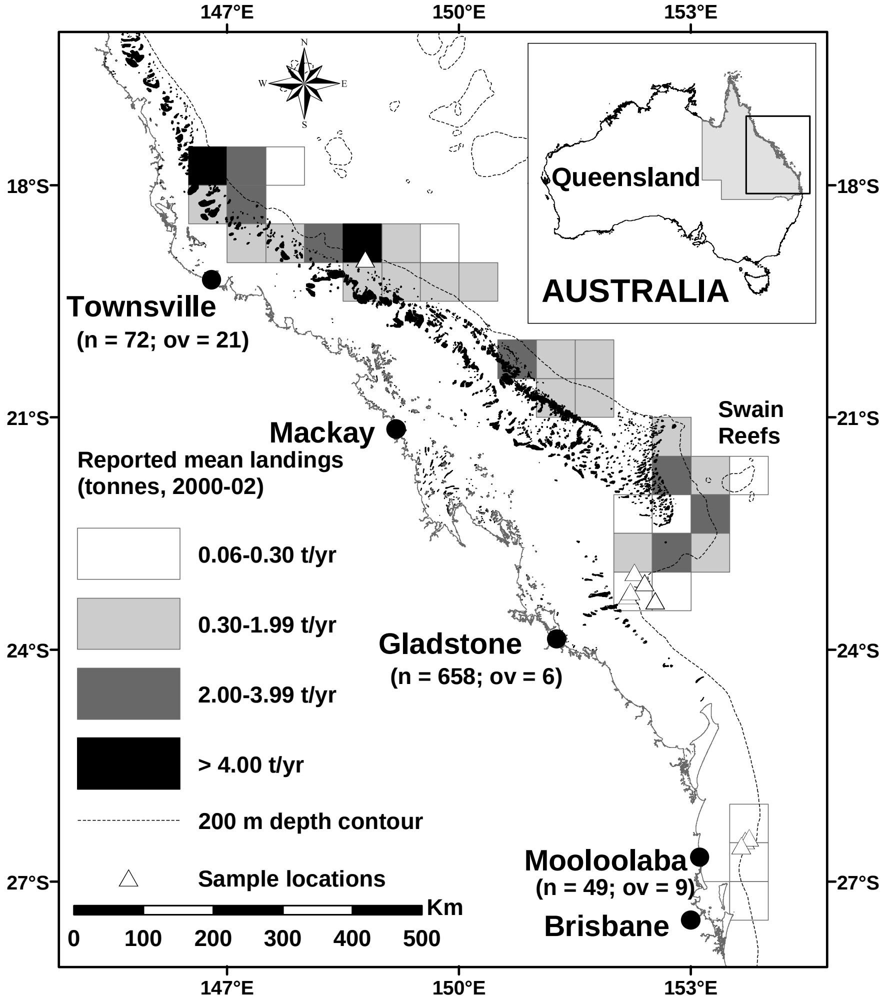


Figure 13.3.1. Spatial distribution of reported mean landings of *Linuparus trigonus* (Von Siebold, 1824), from the Queensland East Coast Trawl Fishery (2000-02). Logbook grids that reported < 0.06 t year^{-1} (< 1% of reported catches) have been omitted for clarity. Sample numbers (ov = ovigerous) for each location area are detailed in parentheses.

Specimens were frozen and stored until processed in the laboratory. Once thawed, total weight (TW; antennal flagella removed), carapace length (CL), sex, gonad weight (females only), macroscopic gonad condition, ovigerous setae, and stage of egg development were recorded. Carapace length was measured between the mid-point of the sub-orbital horns to the posterior edge of the carapace using graduated Vernier callipers to 0.1 mm. Criteria for macroscopic staging of gonads were obtained from Stewart et al. (1997) and are detailed in Table 13.3.1. Extruded eggs were classified as: (1) Early, orange with no pigmentation, (2) Mid, orange with eye-spots visible, or (3) Late, brown with eye-spots visible.

Estimates of brood fecundity were determined using a gravimetric method. Late stage ovigerous females were not used due to the fragility of the eggs. Ovigerous females were placed onto blotting paper and allowed to drain. The entire egg mass was carefully stripped from the pleopods using curved forceps and weighed (± l mg).

Table 13.3.1. Macroscopic gonad descriptions of gonadal development and mean gonadosomatic indices of *Linuparus trigonus* (Von Siebold, 1824)

Stage	Macroscopic description	Mean GSI (range)
1 Immature	Ovaries clear to white, small, straight and narrow. Individual oocytes not visible.	0.12 (0.05 - 0.17) n = 5
2 Immature / regressed	Ovaries cream to yellow and small. Individual oocytes not visible.	0.65 (0.11 - 1.23) n = 79
3 Maturing	Ovaries orange, enlarged throughout their length but not convoluted. Individual oocytes are just visible through the ovary wall.	1.62 (0.69 - 2.53) n = 43
4 Mature	Ovaries bright orange, swollen and convoluted filling all available space in the cephalothoracic region. Individual oocytes are clearly visible through the ovary wall.	5.98 (2.99 - 10.14) n = 53
5 Spent	Ovaries cream to yellow/orange, large but not convoluted, with flaccid and granular appearance. A few residual oocytes can sometimes be seen through the ovary wall.	1.03 (0.19 - 2.75) n = 17

Between 20 and 500 mg of the egg mass was sub-sampled, weighed (± 0.01 mg) and fixed in 70% ethanol. Fecundity sub-samples averaged 251.3 ± 27.21 (S.E.) mg and varied between 0.23 and 5.88% of the total egg mass weight (mean = 2.23%). Eggs clumps in the sub-sample were separated into individual eggs by dissolving the egg stalks with sodium hypochlorite. Once separated, the sub-sample was drained, rinsed, and resuspended in 70% ethanol, poured into a glass Petri dish and scanned at 300 dpi. The total number of eggs in the sub-sample was then determined using computer image analysis (Image-Pro Plus, version 4.5). Fecundity was estimated by simple proportion. The mean diameters of freshly thawed individual eggs were determined from 13 females using a dissecting microscope fitted with a digital camera and measured using image analysis software. Diameter measurements were taken radiating at 2 degree intervals for each egg to produce a mean egg diameter. Between 10 and 38 eggs were measured for each female.

13.4 RESULTS

13.4.1 Analysis of logbook data

The spatial distribution of mean annual landings of *L. trigonus* from 2000 to 2002 is shown in Figure 13.3.1. Annual landings for the QECTF in 2000, 2001, and 2002 were 103.4, 50.2, and 13.5 tonnes, respectively. The majority of the catch came from seasonal trawling in the deep waters (> 90 m) off Townsville, however, substantial catches were also reported off Mackay and at the Swain Reefs (Figure 13.4.1a). Off Townsville and Mackay, total annual trawl effort was 825, 294, and 0 boat days and 131, 3, and 0 boat days in 2000, 2001, and 2002, respectively (Figure 13.4.1b). In contrast, total annual effort remained relatively stable at the Swain Reefs and was 3099, 2916, and 3640 boat-days for 2000, 2001, and 2002, respectively. Overall, the total catch-per-unit effort (CPUE) was high off Townsville and Mackay with an average catch rate of 194 and 115 kg per boat-day, respectively, whereas the average catch rate at the Swain Reefs was only 9.15 kg per boat-day (Figure 13.4.1c). Small isolated catches were also reported off the south-eastern coast of Queensland.

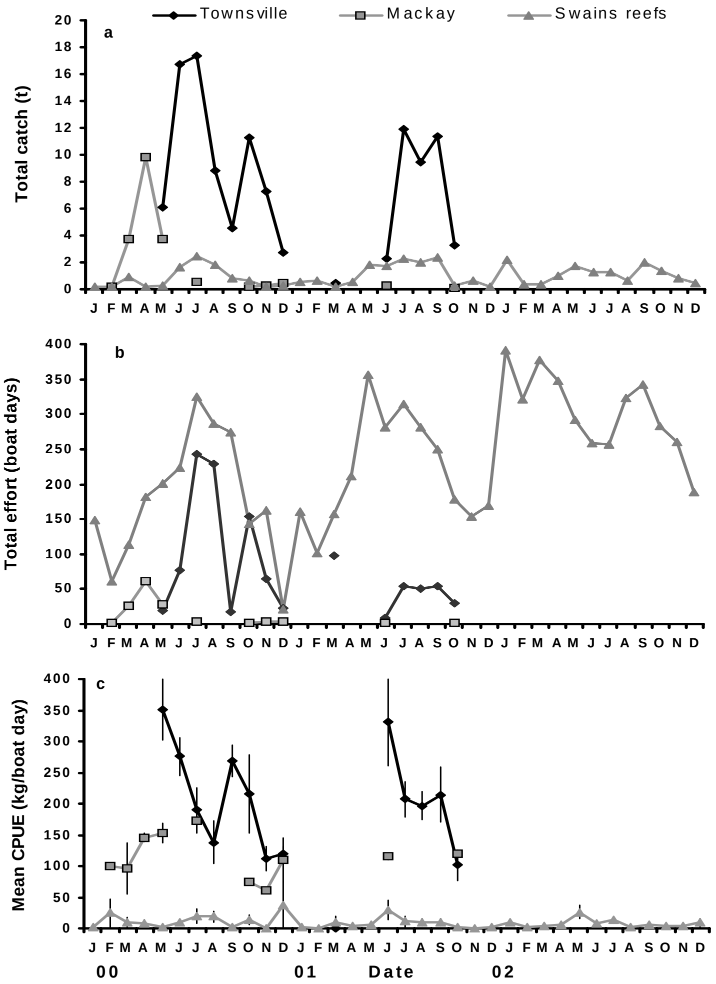


Figure 13.4.1. a, Monthly total catch; b, total effort; and, c, catch-per-unit effort of *Linuparus trigonus,* (Von Siebold, 1824), between January 2000 and December 2002 along Queensland's east coast. Logbook grids that reported < 0.3 t per year (< 5% of reported catches) have been omitted for clarity.

13.4.2 Sex ratio and length-frequency distributions

A total of 434 females and 345 males was collected. The length-frequency distribution of male and female lobsters (locations pooled) displayed multi-modal distributions (Figure 13.4.2). The percentage of female to male lobsters was relatively stable throughout the small size classes (30 to 70 mm CL) and ranged between 50.0 and 63.6% females, however, female proportions rose markedly in size classes between 75 and 90 mm ranging between 72.2 and 85.4%. In size classes greater than 95 mm, males were numerically dominant. Overall, females outnumbered males by 1.19:1. The length-weight relationship for males and females (antennal flagella removed) was $TW = 0.00034*CL^{2.9812}$ (n = 285, $r^2 = 0.99$), and $TW = 0.00038*CL^{2.9629}$ (n = 310, $r^2 = 0.99$) respectively.

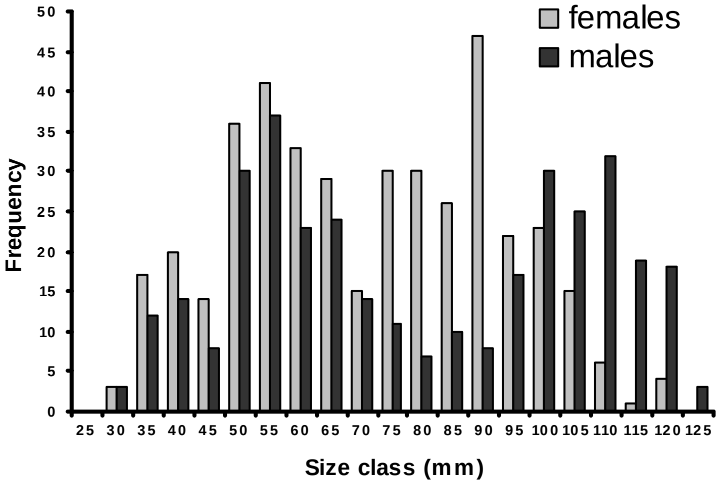


Figure 13.4.2. Size-frequency distributions of male and female *Linuparus trigonus* (Von Siebold, 1824). Values on the x-axis are maximum values for each 5 mm size class interval.

13.4.3 Size at maturity

The relationship between female size and ovarian development is detailed in Figure 13.4.3. Females smaller than 58 mm CL possessed immature ovaries. Thereafter, the proportion of immature stages declined markedly until all females larger than 75 mm CL possessed ovaries at stage 2 or higher. The smallest sexually mature female (stages 3–5) was 59.8 mm CL. This individual was ovigerous. The proportion mature did not exceed 50% until lobsters were larger than 80 mm CL, however, the frequency of ovigerous lobsters was highest in sizes of 75 to 85 mm CL (Figure 13.4.4). Lobsters possessing mature ovaries or ovigerous setae were present in all three locations sampled (Figure 13.3.1).

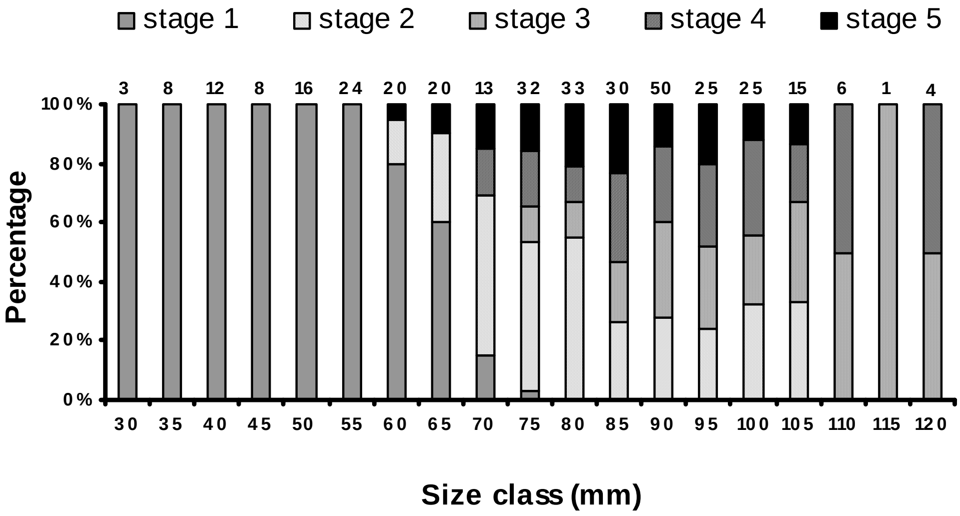


Figure 13.4.3. Proportions of female *Linuparus trigonus* (Von Siebold, 1824) in relation to size and ovarian maturation

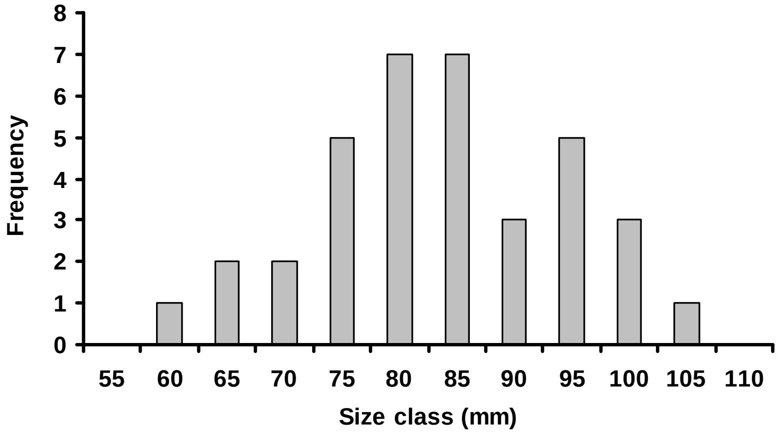


Figure 13.4.4. Size-frequency distribution of ovigerous *Linuparus trigonus* (Von Siebold, 1824)

13.4.4 Size-specific brood fecundity and egg size

The brood fecundity (BF) of 32 females varied from 19,287 to 100,671 eggs for females of 59.8 to 104.3 mm CL. Ovigerous females were obtained from August, October, February, March, and April. Brood fecundity was best described by the power equation, $BF = 0.1107*CL^{2.9241}$ ($r^2 = 0.74$) (Figure 13.4.5). A double log-linear fit ($\log_{10} BF = 2.7879*\log_{10}CL -0.6877$, $r^2 = 0.66$) of the data and raw linear fit ($BF = 1551.9*CL -79{,}532$, $r^2 = 0.63$) had slightly lower r^2 but are provided for comparison with most other lobster size-fecundity relations.

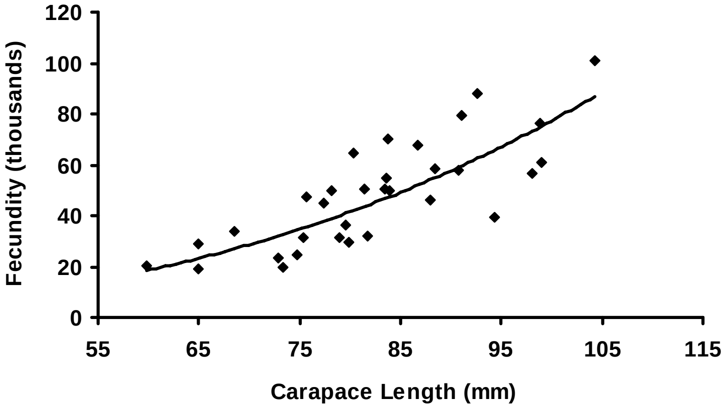


Figure 13.4.5. Scatterplot regression of brood fecundity and carapace length of *Linuparus trigonus* (Von Siebold, 1824)

Egg size and weight ranged from 0.96 to 1.12 mm (mean = 1.02 ± 0.01 mm) and 0.28 to 0.77 mg (mean 0.51 ± 0.021 mg) respectively. Both egg weight and size were independent of lobster size. The mean number of eggs per gram body weight for ovigerous females was 245 ± 10 egg g^{-1} (range 135–388).

13.5 DISCUSSION

The results from this study are the first published accounts of brood fecundity for lobsters of the genus *Linuparus*. The minimum carapace size for which we were able to describe fecundity was limited to the smallest ovigerous female (59.8 mm CL). As no other females possessed mature gonads below this size and the largest ovigerous female was close to the maximum size encountered (only 2.8% of females were larger than 104 mm CL), the brood fecundity–size relationship is likely to represent the true limits of the species. The results indicated that ovigerous *L. trigonus* carry approximately 20,000–100,000 eggs and that the number of eggs in the brood is size dependent. The positive curvilinear relationship (Figure 13.4.5) between carapace length and brood fecundity in *L. trigonus* is similar to those described for other spiny lobsters (Chubb, 1994; Quackenbush, 1994). The broad geographical range that ovigerous and mature lobsters were collected from indicates that *L. trigonus* is reproductively active along Queensland's east coast between Townsville and Moolooaba. Geographical variation in fecundity and size at maturity has been reported in several lobster species (Plaut, 1993; Chubb, 1994; Pollock, 1997; Mori et al., 1998). However, examination of the potential geographical differences in size at maturity and brood fecundity in *L. trigonus* in this study was not possible due to low sample numbers. Therefore, the brood fecundity–size relationship presented here should be viewed as a general relationship for Queensland's *L. trigonus* population. Our findings that egg weight and egg size were independent of lobster size is consistent with other published lobster studies (Pollock, 1997; Stewart and Kennelly, 1997; Demartini and Williams, 2001). This indicates that, as suggested by Stewart and Kennelly (1997), eggs from small lobsters are equally as viable as eggs from large lobsters. Comparisons of egg sizes between lobster species are usually represented as an inverse index of egg size and expressed as the number of eggs per gram body weight (Pollock, 1991, 1997). Results from the present study show that the mean number of eggs per gram body weight is relatively low (250 egg g^{-1}) compared to other spiny lobsters (300–800 egg g^{-1}; Pollock, 1997). Larger egg size in spiny lobsters is directly related to hatching phyllosoma size. The relatively large egg size of *L. trigonus* suggests that phyllosoma larvae exhibit some abbreviation of development. *Linuparus* phyllosoma hatch in an advanced stage, measuring between 2.40 and 2.55 mm at hatching, and therefore may have a short duration of larval development compared to other spiny lobster species (Kim, 1977; Baisre, 1994). Larval duration in deep water *Palinurus* spp. is markedly shorter than the shallower *Jasus* and *Panulirus* spp., resulting in reduced larval mortality (Kittaka et al., 1997). Pollock (1997) suggested that the larger egg size in *Palinurus* spp. may be related to the deep water settling behaviour of the puerulus, which could subsequently reduce mortality rates of newly settled stages by reducing predation pressures. Interestingly, anecdotal evidence from commercial fishers and unpublished research data (Ward, unpubl.) suggests that the abundance of small *L. trigonus* increases with depth. Ward (unpubl.) suggested that higher juvenile abundance with depth could be related to predation pressures decreasing with depth or result from a shoreward migration of juveniles after settlement in deeper waters off the continental shelf.

The smallest sexually mature lobster measured 59.8 mm CL with 50% maturity (stages 3–5) between 80–85 mm CL. However, it is important to understand that due to the cyclic nature of gonad development in spiny lobsters (Kim, 1977; Aiken and Waddy, 1980), stage 2 includes individuals maturing for the first time and mature lobsters in a regressed state of reproduction. Therefore, Figure 13.4.3 is likely to slightly overestimate the size at 50% maturity. *Linuparus somniosus* (Berry and George, 1972) mature at a much larger size than *L. trigonus,* with ovigerous females ranging from 96.1 to 130.9 mm CL and 50% of females measuring above 110 mm CL (n = 14; Wowor, 1999).

Some spiny lobsters are known to produce multiple broods, where the ovaries mature while the female is ovigerous (Minagawa and Sano, 1997). In the present study all of the ovigerous females possessed spent ovaries, including mid- and late stage ovigerous females. In Japanese waters, *L. trigonus* displays an annual reproductive pattern with the mean GSI peaking in July and falling to a minimum in November, with spawning occurring over four months between May and August (Kim, 1977). This suggests that *L. trigonus* in Japanese waters produces a single annual brood. However, as ovigerous animals were present over a broad temporal range in the present study (August, October, February–April), reproductive activity may be protracted in Queensland’s population, possibly due to higher seawater temperatures. Further investigations are required to determine the seasonality of reproduction, incubation period, and brood frequency in Queensland’s *L. trigonus* populations.

Results from the present study indicate that at the size of female maturity (> 75 mm CL) females are more abundant than males. However, at larger size classes (> 100 mm CL) males dominate. This could indicate that at the onset of sexual maturity female growth slows, resulting in males numerically dominating the larger size classes. Gender-related differences in growth rates have been reported for other spiny lobsters (Groeneveld, 1997; Hooker et al., 1997; McGarvey et al., 1999), and are usually related to mature females displaying longer intermoult periods and smaller moult increments than mature males (Aiken, 1980; Jong, 1993). Alternatively, behavioural changes at the onset of sexual maturity could result in reproductively active females being more susceptible to trawl capture, which could explain why females dominated between 75 and 95 mm CL.

The distribution of catches of *L. trigonus* highlights that this species is distributed along Queensland's east coast. The high catch rates off Townsville and Mackay indicate that in these areas lobster abundance is high enough to justify targeted fishery effort, however, effort in these areas is highly seasonal. In contrast to the *L. trigonus* trawl grounds off Townsville and Mackay, the catch rates at the Swain Reefs and southwards represent incidental catch while trawling for eastern king prawns *Penaeus plebejus* (Hess, 1865). Recent changes in the QECTF legislation prevent commercial trawlers from targeting *L. trigonus.* Consequently, in the target fisheries off Townsville and Mackay, trawl effort has dropped markedly over the last three years and resulted in a significant reduction in the total reported catch of *L. trigonus.* Currently, the only management measure is a prohibition on retaining ovigerous females. Minimum legal sizes (MLS) are yet to be introduced as the optimum MLS is yet to be determined. MLS are often set to ensure lobsters breed at least once before recruitment to the fishery or at 50% maturity levels (Chubb, 1994). Tools which assist in determining appropriate MLS limits include yield- and egg-per-recruit analyses, however, these methods require estimation of growth, natural mortality and fishing mortality rates, which are currently unknown for *L. trigonus*. Therefore future research on *L. trigonus* should concentrate on estimating these parameters as well as determining the seasonality of reproduction, the frequency of spawning, the percentage of egg loss during incubation and larval survival.

13.6 REFERENCES

Aiken, D.E., 1980. Moulting and growth. In: Cobb J.S., Phillips B.F., (eds.), The biology and management of lobsters. Academic Press, New York 1, pp. 91-163.

Aiken, D.E., Waddy, S.L., 1980. Reproductive biology. In: Cobb J.S., Phillips B.F., (eds.), The biology and management of lobsters. Academic Press, New York. 1, 215-276.

Berry, P.F., George, R.W., 1972. A new species of the genus *Linuparus* (Crustacea, Palinuridae) from south-east Africa. Zool. Meded. Leiden. 46, 17-23.

Baisre, J.A., 1994. Phyllosoma larvae and the phylogeny of Palinuroidea (Crustacea: Decapoda): a review. Australian J. Mar. Freshwat. Res. 45, 925-944.

Bruce, A.J., 1965. A new species of the genus *Linuparus* White, from the South China Sea (Crustacea Decapoda). Zool. Meded. Leiden. 41, 1-13.

Chubb, C.F., 1994. Reproductive biology: issues for management. In: Phillips, B.F., Cobb J.S., Kittaka J., (eds.), Spiny Lobster Management. Blackwell Scientific Publications, Carlton, Victoria. 181-212.

Demartini, E.E., Williams, H.A., 2001. Fecundity and egg size of *Scyllarides squamosus* (Decapoda: Scyllaridae) at Maro Reef, northwestern Hawaiian Islands. J. Crust. Biol., 21, 891-896.

Groeneveld, J.C., 1997. Growth of spiny lobster *Palinurus gilchristi* (Decapoda: Palinuridae) off South Africa. South African J. Mar. Sci. 18, 19-29.

Hill, B.J., Wassenberg, T.J., 1990. Fate of discards from prawn trawlers in Torres Strait. Aust. J. Mar. Freshwat. Res. 41, 53-64.

Holthuis, L.B., 1991. FAO species catalogue 13. Marine lobsters of the world. An annotated and illustrated catalogue of the species of interest to fisheries known to date. FAO Fisheries Synopsis. Rome. 125, 111-114.

Hooker, S.H., Jeffs, A.G., Creese, R.G., Sivaguru, K., 1997. Growth of captive *Jasus edwardsii* (Hutton) (Crustacea: Palinuridae) in north-eastern New Zealand. Mar. Freshw. Res. 48, 903-910.

Jong, K.J., 1993. Growth of the spiny lobster *Panulirus homarus* (Linnaeus, 1758), depending on sex and influenced by reproduction (Decapoda, Palinurisae). Crustaceana. 64, 18-23.

Kim, C.H., 1977. Gametogenesis and early development of *Linuparus trigonus* (Von Siebold). Bull. Korean Fish. Soc. 10, 71-96.

Kittaka, J., Fernando, A., Abrunhosa, A., 1997. Characteristics of palinurids (Decapoda;Crustacea) in larval culture. Hydrobiologia. 358, 305-311.

McGarvey, R., Ferguson, G.J., Prescott, J.H., 1999. Spatial variation in mean growth rates at size of southern rock lobster *Jasus edwardsii* in South Australian waters. Mar. Freshw. Res. 50, 333-342.

Minagawa, M., Sano, M., 1997. Oogenesis and ovarian development cycle of the spiny lobster *Panulirus japonicus* (Decapoda: Palinuridae). Mar. Freshw. Res. 48, 875-887.

Mori, M., Biagi, F., De-Ranieri, S., 1998. Fecundity and egg loss during incubation in Norway lobster *Nephrops norvegicus* in the north Tyrrhenian Sea. J. Nat. Hist. 32, 1641-1650.

Plaut, I., 1993. Sexual maturity, reproductive season and fecundity of the spiny lobster *Panulirus penicillatus* from the Gulf of Eilat (Aqaba), Red Sea. Aust. J. Mar. Freshw. Res. 44, 527-535.

Pollock, D.E., 1991. Population regulation and stock-recruitment relationships in some crayfish and lobster populations. In: Wenner, A., Kuris, A., (eds.), Crustacean issues 7. AA Balkema, Rotterdam. Crustacean egg production. 247-266.

Pollock, D.E., 1997. Egg production and life-history strategies in some clawed and spiny lobster populations. Bull. Mar. Sci. 61, 97-109.

Quackenbush, L.S., 1994. Lobster reproduction: A review. Crustaceana. 67, 82-94.

Stewart, J., Kennelly, S.J., 2000. Growth of the scyllarid lobsters *Ibacus peronii* and *I. chacei*. Mar. Biol. 136, 921-930.

Stewart, J., Kennelly, S.J., Hoegh-Guldberg, O., 1997. Size at sexual maturity and the reproductive biology of two species of Scyllarid lobsters from New South Wales and Victoria, Australia. Crustaceana. 70, 344-367.

Wowor, D., 1999. The spear lobster *Linuparus somniosus* Berry and George, 1972 (Decapoda, Palinuridae) in Indonesia. Crustaceana.72, 673-684.

14 The biology, population dynamics and minimum legal size of three spot crabs *Portunus sanguinolentus*

A. J. Courtney and J. A. Haddy

14.1 ABSTRACT

This chapter describes the reproductive biology, growth and mortality rates of three spot crabs *Portunus sanguinolentus* and uses these parameters in a yield-per-recruit analysis to determine the optimum age and size at which the crabs should be harvested. The crabs attain maximum size at about 3.5 years of age. Estimates of the instantaneous rate of total mortality were 1.13 per year for males and 1.61 for females. In the absence of more robust mortality rate estimates, we assumed that natural mortality and fishing mortality rates were equal, implying that exploitation was at 0.5. The optimum age at first capture was determined by combining the yield of both sexes. Where possible, for the yield-per-recruit analysis, we incorporated uncertainty in the parameter estimates by re-sampling from probability distributions of growth and mortality rates. The optimum age at which three spot crabs should be harvested was estimated to 0.88 years which, using a derived composite growth curve, equates closely to 100 mm carapace width. The analysis assumes that both males and females experience fishing mortality. Male and female three spot crabs were found to reach sexual maturity at a carapace width of 81 and 89 mm respectively, and once mature breed throughout the year with a peak of activity between spring and summer. Additional estimates of the key population parameters, including a) growth rates, b) mortality rates, and c) post-release survival rates may improve over time with more research and this is likely to affect the estimated optimum size at capture.

14.2 INTRODUCTION

Three spot crabs *Portunus sanguinolentus* are distributed throughout the Indo-West Pacific region and typically inhabit sandy oceanic habitats (Sumpton et al., 1989). In southeastern Queensland three spot crabs form an incidental component of trawl and pot fisheries. The Management Plan report “Permitted Fish (other than principal fish) and Steaming Day Review Paper”, by the Queensland Fisheries Service (August 2001), stated that 80% of Queensland’s trawl operators reported catching three spot crabs, with a total harvest of 21 tonnes during 2000, worth approximately $105,000. However, these figures are very preliminary and should be considered with caution. The value of the incidental pot catch of three spot crabs is unknown, but likely to be a significant income supplement to pot fishers.

Currently, there are no management measures pertaining to the species in Queensland coastal waters. Because three spot crabs are not targeted and are only a byproduct (i.e., permitted species), management strategies such as spatial and temporal closures and gear restrictions are not applicable. Portunid crabs form extensive fisheries around the world and a substantial amount is known about their biology. Male and female three spot crabs in Queensland are known to reach sexual maturity at a carapace width of 83 and 74 mm respectively (Sumpton et al., 1989). Within Indian waters three spot crabs have a size-dependent fecundity ranging from 44,000 to 1.2 million eggs (Sukumaran and Neelakantan, 1997a) and an extended spawning period between August to May. Similarly, Campbell and Fielder (1986) reported catching ovigerous females between August to April off Moreton and North Stradbroke Islands with more than 50% of females being ovigerous between mid-October to early February.

Crabs are relatively robust animals and are reported to have high survival rates after being captured in trawl nets (Hill and Wassenberg, 2000). Therefore, due to their apparently low discard mortality, the introduction of a minimum legal size is one of the few practical means of managing the stock and preventing growth and recruitment overfishing. This chapter quantifies key population parameter estimates of three spot crabs, specifically growth, mortality and seasonal variation in reproductive biology, and undertakes a yield-per-recruit analysis to derive an optimum minimum legal size.

14.3 METHODS

14.3.1 Sampling the crabs

Fishery-dependent monthly samples of three spot crabs were collected between November 2001 and January 2003. The samples were dependent on commercial fishers operating from Mooloolaba and Tin Can Bay donating samples. Samples were frozen and stored until processed in the laboratory. Once thawed, total weight, carapace length, carapace width, sex, maturity, damage and the presence of an egg mass were recorded. As fishers target more valuable species throughout the year, sample numbers declined or were absent in some months, making the estimation of growth and mortality rates from length-frequency analysis unreliable. As a result, a more complete and larger dataset obtained from Sumpton et al. (1989) was used to estimate the growth and mortality (both natural and fishing mortality) rates required for the yield per recruit analysis. Wherever possible, uncertainty in the population parameter estimates was included for the yield-per-recruit analyses.

14.3.2 Parameter estimation

The standard length-weight relationship was determined for undamaged individuals of each sex:

$$Weight(grams) = a.Carapace\ width\ (mm)^{b}$$

where a and b are constants. The standard errors of these constants, obtained from regression analysis, were used to generate probability distributions for each. The yield-per-recruit analyses used an estimate of the weight at L_∞ and the probability distributions were used to estimate a range of possible values of the weight at L_∞. Thus, rather than using a single point estimate of the weight at L_∞, a range of values was used.

Estimates of the von Bertalanffy growth curve parameters, K and L_∞, were derived from monthly length-frequency data using the automatic search option for K in the computer program FiSAT (Gayanilo, Sparre and Pauly, 1994). Additional published estimates of the growth parameters, mainly from India (Sukumaran and Neelakandan, 1997b, Sarada, 1998) were also considered and used to derive a composite growth curve. This was achieved by estimating the mean values of all estimates of K and L_∞ using both our own derived estimates and the published estimates. The values of K and L_∞ and the mean estimates were presented in an auximetric plot. Again, the standard errors of these means were used to generate probability distributions of K and L_∞ that were used in the yield-per-recruit analysis.

The instantaneous rate of total mortality Z was estimated using the length-converted catch curve method (Sparre and Venema, 1992). At present we have no robust estimate of the instantaneous rate of natural mortality M for three spot crabs in Queensland. We therefore assumed that fishing mortality F and natural mortality M were equal and therefore that the level of exploitation was 0.5 (F/Z).

14.3.3 Yield-per-recruit analysis

A stochastic version of the Beverton and Holt yield-per-recruit method was used to determine the age, and then size, at which yield of the stock would be maximised. The basic form of the model is:

$$Y/R = \exp(-M(t_c - t_r)) \sum_{i=t_c}^{i=t_l} \left\{ (F/(F+M)) \exp(-(F+M)(i-t_c))\,(1-\exp(-(F+M)))W_i \right\}$$

where Y = steady state yield of the fishery, R = number of recruits, M = instantaneous rate of natural mortality, F = instantaneous rate of fishing mortality, W_i = mean weight of fish aged i, t_r = age at recruitment to fishable stock, t_c = actual age of first capture, t_l = maximum age of fish in stock. Some assumptions underlie the equilibrium yield per recruit:

(i) recruitment is constant, yet not specified (hence the phrase “yield per recruit”)
(ii) all fish (crabs in the present study) of a cohort are hatched on the same date
(iii) fishing and natural mortalities are constant over the post-recruitment phase
(iv) fish older than t_l make no contribution to the stock.

A range of values, selected from probability distributions, were used for M (natural mortality), F (fishing mortality) and the von Bertalanffy growth parameters K and L_∞ [used to estimate W_i (mean weight of crab aged i)]. The standard errors of the length-weight constants a and b were incorporated to consider the variability in the weight of individuals. The values and range of these distributions are provided in Figure 14.4.7

The yield per recruit was estimated for each sex separately because males and females have different growth, mortality and length-weight parameters. Estimated yields for the two sexes were then combined and the age at which maximum yield occurred was recorded. A total of 1000 simulations were undertaken resulting in 1000 estimates of the age at which yield is maximised. The median value of this distribution of ages was then converted to a length using a combined unisex age-length relationship.

14.4 RESULTS AND CONCLUSIONS

14.4.1 Length frequencies, morphometrics and reproductive biology

A total of 1392 male and 806 female crabs were donated (Figure 14.4.1). The length-frequency distributions of male and female crabs highlighted that males attain a larger size than females with males reaching 185 mm carapace width (CW) and 371 g compared to 154 mm CW and 223 g for females.

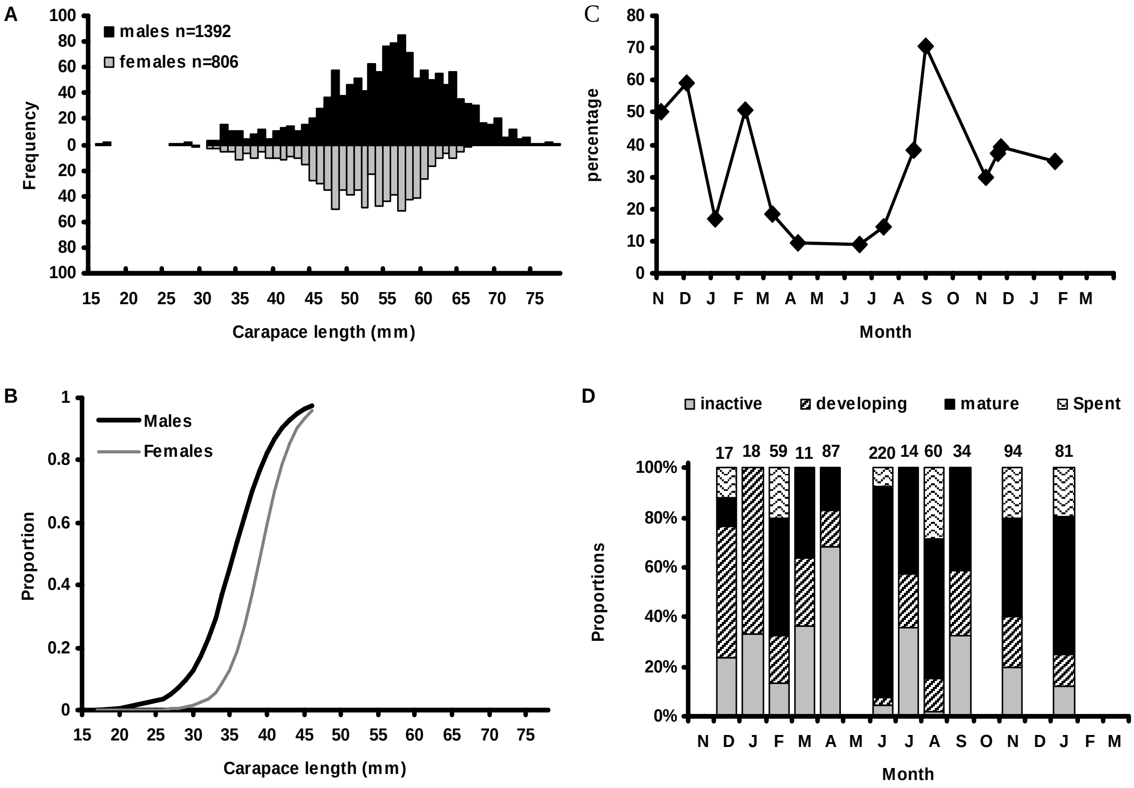


Figure 14.4.1. Male and female length-frequency distributions: (A) size at maturity curves; (B) seasonal trends in the presence of ovigerous females; and (C) seasonal changes in ovarian maturity; (D) for three spot crabs *Portunus sanguinolentus* donated between November 2001 and January 2003.

Morphometric relationships for a) carapace length vs carapace width and b) carapace length vs total weight are provided in Table 14.4.1. Seasonal reproductive data indicated that vitellogenesis and spawning occurs throughout the year with developing and fully mature ovaries present year round. This is also supported by the fact the ovigerous females were present in all months sampled. However, reproductive activity, based on the presence of ovigerous crabs, was highest in September and remained relatively high until March. Size-at-maturity data indicated that males mature at 35.6 mm CL (81.4 CW) and females at 39.2 mm CL (89.2 CW). The results for the males were similar to those of Sumpton et al. (1989), but the size-at-maturity for females (i.e., 89.2 mm CW) was considerably larger than that found by Sumpton et al. (i.e., 74 mm CW).

Table 14.4.1. Morphometric regression relationships for three spot crabs *Portunus sanguinolentus*

		TW = $a*CL^b$			CW = a*CL-b			CL_{MAX}
	N	**a**	**b**	r^2	**a**	**b**	r^2	**mm**
Males	529	0.000478	3.1066	0.97	2.291	-0.1463	0.95	77.6
Females	385	0.000502	3.0883	0.95	2.0838	7.4989	0.92	70.3
Combined	914	0.000467	3.109	0.97	2.1816	2.487	0.94	77.6

14.4.2 Growth

Males attain a greater size than females. This is reflected not only in the length-frequency distributions (Figure 14.4.1) but also in the estimates of L_∞ (Table 14.4.2). This is consistent with the studies by Sukumaran and Neelakandan (1997b) and Sarada (1998) in Indian waters. The L_∞ values reported in Indian waters are larger than those derived here. The reason for this difference is unknown, but possibly due to limitations on the size and geographic range of the Queensland samples used here. In general, the samples used here were obtained from relatively shallow inshore areas in Moreton Bay and off Bribie Island. A more comprehensive sampling program which incorporates offshore waters might include larger individuals that would increase the estimates L_∞.

Table 14.4.2. Published and estimated values of K and L_∞ for *Portunus sanguinolentus*

Reference/method	**L_∞**	**K**
Sarada (1998) males	172.9	1.494
Sukumaran and Neelakandan (1997b) males	195.0	0.990
Elefan (FiSAT) Males	158.0	0.790
Mean Males	**174.6 (S.E. 10.8)**	**1.053 (S.E. 0.301)**
Sarada (1998) females	161.8	1.574
Sukumaran and Neelakandan (1997b) females	188.0	0.820
Elefan (FiSAT) Females	142.0	0.570
Mean Females	**162.9 (S.E. 13.3)**	**0.903 (S.E. 0.209)**

The estimates of the growth coefficient K based on the length-frequency analysis of the Sumpton et al. (1989) data were 0.79 per year for males and 0.57 per year for females. Estimates of L_∞ were 158 mm CW for males and 142.0 mm CW for females. These estimates appear to be quite low compared with those published by Sukumaran and Neelakandan (1997b) and Sarada (1998) in Indian waters. The overall mean estimates of K and L_∞ from all three analyses were 1.053 per year and 174.6 mm CW for males and 0.903 per year and 162.9 mm CW for females (Table 14.4.2). A distribution of the values and overall means is provided in the auximetric plot (Figure 14.4.2).

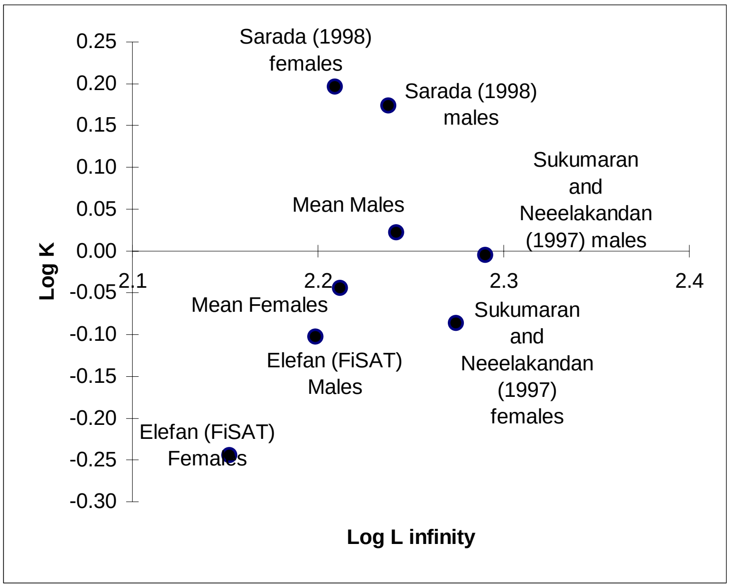


Figure 14.4.2. Auximetric plot of K and L_∞ for male and female *Portunus sanguinolentus*

The mean growth rates, derived from all three studies (Sukumaran and Neelakandan, 1997, Sarada, 1998) and the present study, are expressed graphically in Figure 14.4.3. These curves suggest that males attain a slightly larger size than females and have a slightly faster rate of growth. Because length-frequency analysis does not estimate the growth parameter t_0, we used mean estimates of this parameter from Sukumaran and Neelakandan (1997b) and Sarada (1998). These were –0.08 years for females and –0.03 years for males. The maximum size of about 170 mm CW for males and 160 mm CW is obtained in approximately 3.5 years. Estimates of the instantaneous rate of total mortality *Z* were derived using the length-converted catch curve method and the growth parameter estimates for the local (Sumpton et al., 1989) length-frequency data (i.e., not the overall mean growth estimates derived from the auximetric plot). Using these parameter estimates, the estimates of *Z* were 1.13 per year for males and 1.61 per year for females (Figure 14.4.4). Estimates of *Z* reported by Sukumaran and Neelakandan (1997b) in India were much higher at 4.2 per year males and 3.9 per year for females.

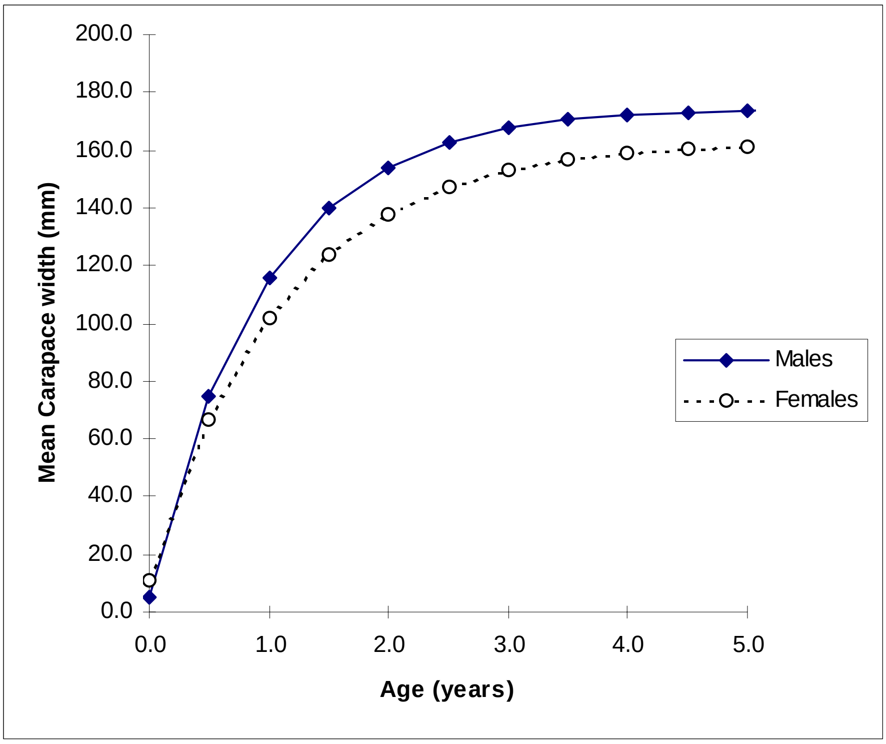
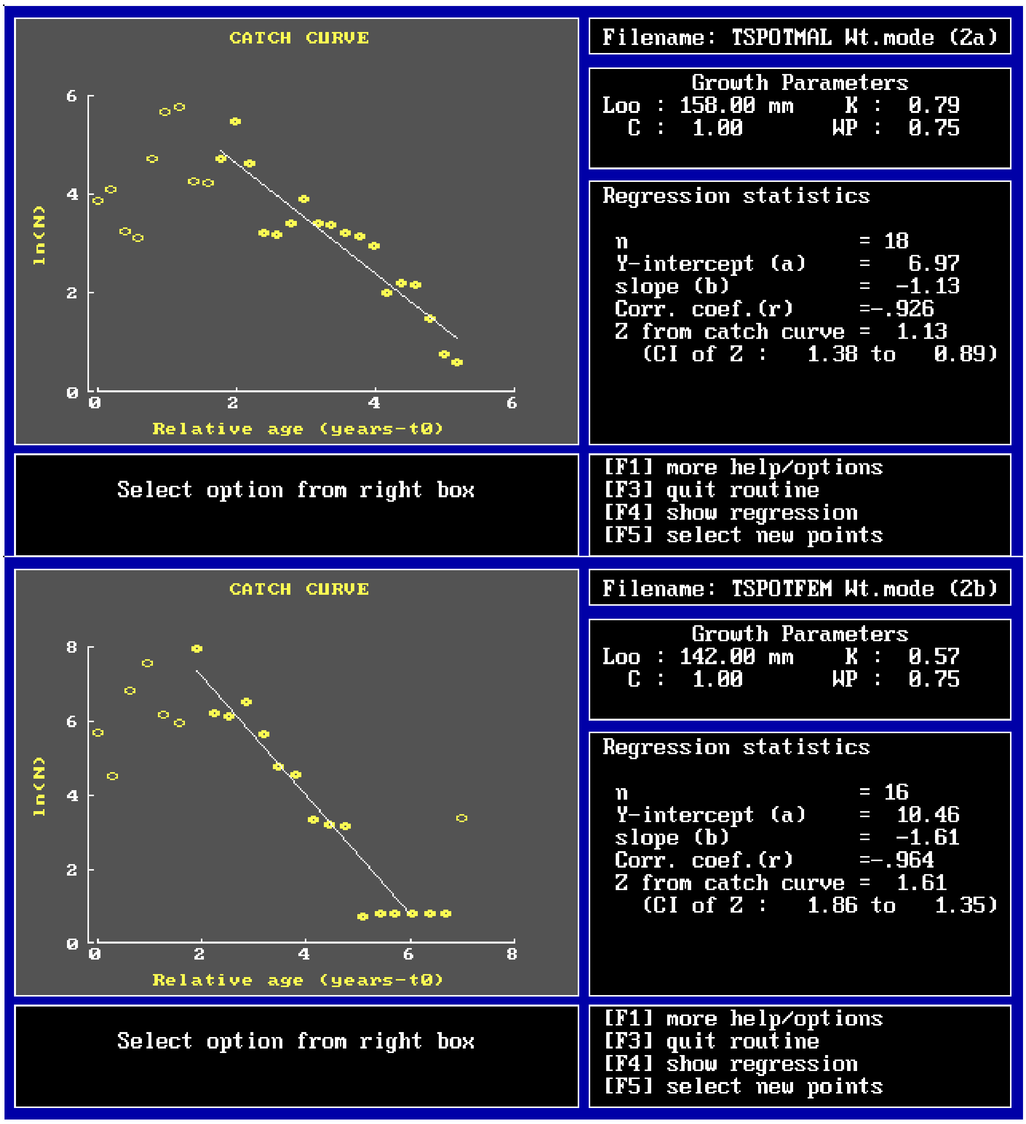


Figure 14.4.3. Definitive von Bertalanffy growth curves for male and female *Portunus sanguinolentus* used in the yield-per-recruit analyses

The instantaneous rate of natural mortality *M* for the local Queensland stock is unknown. Estimates of *M* reported by Sukumaran and Neelakandan (1997b) were 1.6 per year for males and 1.5 for females. We assumed that *M* and *F* were equal for the Queensland stock. Therefore, if we assume a composite estimate of *Z*, based on our male and female *Z*s ((1.13+1.61)/2) of 1.4 per year, and that $Z=F+M$, then *M* must therefore equal 0.7 per year.



```
Filename: TSPOTMAL Wt.mode (2a)

        Growth Parameters
Loo : 158.00 mm     K :  0.79
  C :  1.00        WP :  0.75

Regression statistics

 n                   = 18
 Y-intercept (a)     =   6.97
 slope (b)           =  -1.13
 Corr. coef.(r)      =-.926
 Z from catch curve =  1.13
   (CI of Z :    1.38 to   0.89)

Select option from right box

[F1] more help/options
[F3] quit routine
[F4] show regression
[F5] select new points
```

```
Filename: TSPOTFEM Wt.mode (2b)

        Growth Parameters
Loo : 142.00 mm     K :  0.57
  C :  1.00        WP :  0.75

Regression statistics

 n                   = 16
 Y-intercept (a)     =  10.46
 slope (b)           =  -1.61
 Corr. coef.(r)      =-.964
 Z from catch curve =  1.61
   (CI of Z :    1.86 to   1.35)

Select option from right box

[F1] more help/options
[F3] quit routine
[F4] show regression
[F5] select new points
```

Figure 14.4.4. Length-converted catch curve estimates of *Z* for male (top) and female (bottom) *Portunus sanguinolentus*

14.4.3 Yield-per recruit-analyses

A three-dimensional representation of the yield per recruit for both sexes is provided in Figure 14.4.5. This graph suggests that maximum yield would be obtained when the fishing mortality rate is very high (around 1.5 per year) and if the crabs were first captured and harvested at 1.1 years of age. However, fishing mortality is unlikely to be this high and our estimate of fishing mortality is 0.7 per year. At this level of fishing mortality, yield would be maximised at an age of first capture ranging from 0.5–1.5 years of age (Figure 14.4.5).

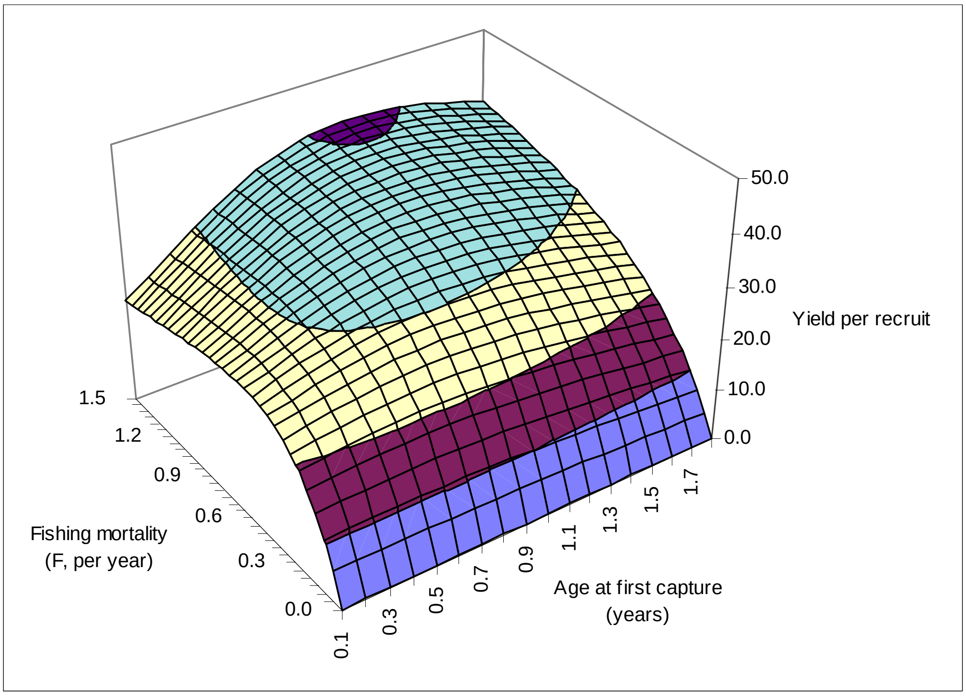


Figure 14.4.5. Beverton and Holt yield-per-recruit model for *Portunus sanguinolentus*. Assuming an instantaneous rate of fishing mortality of approximately 0.7 per year, the optimum age at first capture is between 0.5 and 1.5 years.

14.4.4 Estimating the optimum age (and size) at first capture

When the variation in several of the parameter estimates was taken into account, the optimum age (based on the median of the distribution of the optimum age at first capture in Figure 14.4.6) for the combined yields of males and females was estimated to be 0.88 years. The simulations were undertaken by re-sampling from distributions of the parameters. The instantaneous rates of both fishing mortality F and natural mortality M were assumed to vary from 0.5 to 1.0 per year and were assumed to be uniformly distributed. The von Bertalanffy growth parameter K was assumed to vary according to a normal probability distribution with a mean of 0.9 per year and a standard deviation of 0.52 per year. The male values for K also assumed a normal probability distribution with a mean of 1.05 per year and a standard deviation of 0.36 per year. The weight of males and females at L_∞ was also assumed to vary according the estimates and standard errors of the length-weight constants a and b. The mean optimum age was 0.93 years (Figure 14.4.6). However, because the distribution was not normally distributed, we chose to use the median value (0.88 years) rather than the mean. From the growth curves of Figure 14.4.3, this equates to a carapace width of 94.4 mm CW for females and 107.6 mm CW for males. Since it would be impractical to impose two minimum legal sizes (one for each sex), a single minimum legal size, based on the average of these two carapace widths was chosen. This equates to 101 mm CW (which is rounded to 100 mm CW for industry use).

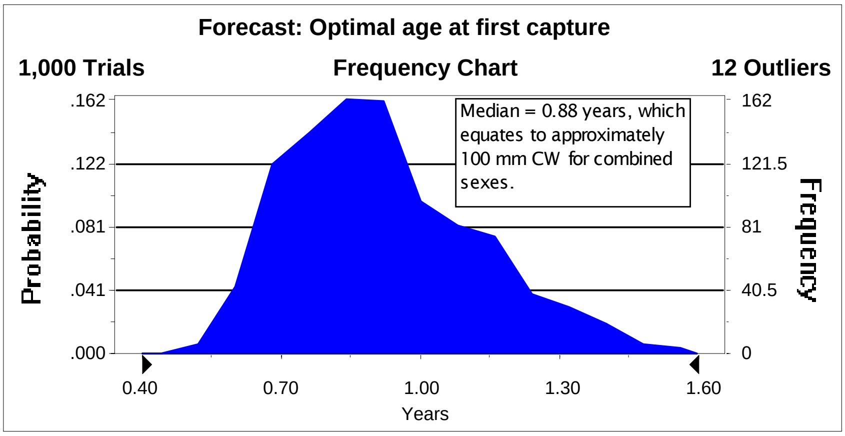


Figure 14.4.6. The distribution of the optimum age at which to harvest *Portunus sanguinolentus* (yields of both sexes have been combined). The median occurs at 0.88 years which equates to approximately 100 mm carapace width. This simulation takes account of the both sexes and the variability in growth parameters (K and L_∞), length-weight parameters (a and b), fishing mortality and natural mortality (see parameter assumption distributions below).

The results show that three spot crabs are a relatively short-lived species reaching a maximum age of approximately 3.5 years and that maturity is attained within the first year of life. Reproduction occurs throughout the year with higher activity between spring and summer. Based on the yield-per-recruit analysis, we recommend a minimum legal size of 100 mm CW which would allow fishers to retain marketable crabs while reducing the risk of growth overfishing.

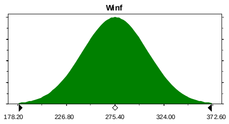
Assumptions

Assumption: Winf **[Three spot Tc opt.xls]Uncertainty - Cell: B6**

Normal distribution with parameters:

Mean	275.40
Standard Dev.	32.40

Selected range is from 179.50 to 371.30
Mean value in simulation was 274.80

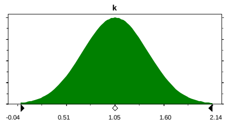


Assumption: k **[Three spot Tc opt.xls]Uncertainty - Cell: B7**

Normal distribution with parameters:

Mean	1.05
Standard Dev.	0.36

Selected range is from 0.00 to 2.13
Mean value in simulation was 1.06

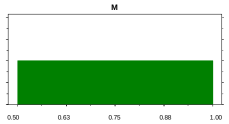


Assumption: M **[Three spot Tc opt.xls]Uncertainty - Cell: B9**

Uniform distribution with parameters:

Minimum	0.50
Maximum	1.00

Mean value in simulation was 0.74

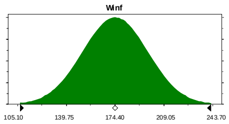


Assumption: Winf **[Three spot Tc opt.xls]Uncertainty - Cell: D6**

Normal distribution with parameters:

Mean	174.40
Standard Dev.	23.10

Selected range is from 106.95 to 242.31
Mean value in simulation was 175.25

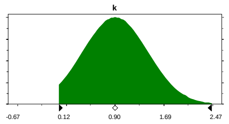


Assumption: k **[Three spot Tc opt.xls]Uncertainty - Cell: D7**

Normal distribution with parameters:

Mean	0.90
Standard Dev.	0.52

Selected range is from 0.00 to 2.45
Mean value in simulation was 0.98

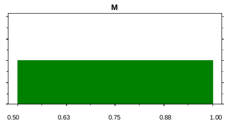


Assumption: M **[Three spot Tc opt.xls]Uncertainty - Cell: D9**

Uniform distribution with parameters:

Minimum	0.50
Maximum	1.00

Mean value in simulation was 0.75



Assumption: tc **[Three spot Tc opt.xls]Uncertainty - Cell: I6**

Uniform distribution with parameters:

Minimum	0.50
Maximum	1.00

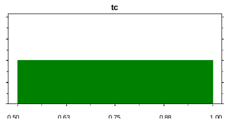


Figure 14.4.7. Distribution assumptions for key population parameter estimates (Weight at L_∞, Winf; Brody growth coefficient, K; and the instantaneous rate of natural mortality, M) for male (top three distributions) and female (next three distributions) three spot crabs, *Portunus sanguinolentus*. The age at which the crabs are first harvested was also assumed to vary and is represented by parameter t_c (bottom distribution).

14.5 REFERENCES

Campbell, G.R., Fielder, D.R., 1986. Size at sexual maturity and occurrence of ovigerous females in three species of commercially exploited portunid crabs in south-east Queensland. Proceedings of the Royal Society of Queensland 97, 79-87.

Gayanilo, F. C., Jr., Sparre, P., Pauly, D., (1994). The FAO-ICLARM Stock Assessment Tools (FiSAT) User's Guide. FAO Computerised Information Series (Fisheries). No. 7. Rome, FAO. 124 p.

Hill, B.J., Wassenberg, T.J., 2000. The probable fate of discards from prawn trawlers fishing near coral reefs: A study in the northern Great Barrier Reef, Australia. Fisheries Research, 48, 277-286.

QFS, 2001. Fisheries (East Coast Trawl) Management Plan 1999. Plan Review Paper, permitted fish (other than principal fish) and steaming day review. DPI publications, Brisbane, Queensland. pp.43.

Sarada, P.T., 1998. Crab fishery of the Calicut coast with some aspects of the population characteristic of *Portunus sanguinolentus*, *P. pelagicus* and *Charybdis cruciata.* Indian Journal of Fisheries, 45, 257-264.

Sparre, P., Venema, S.C., 1992. Introduction to tropical fish stock assessment. FAO, Rome, 376.

Sukumaran, K.K., Neelakandan, B., 1997a. Sex ratio, fecundity and reproductive potential in two marine portunid crabs, *Portunus* (Portunus) *sanguinolentus* (Herbst) and *Portunus* (Portunus) *pelagicus* (Linnaeus) along the Karnataka coast. Indian Journal of Marine Sciences, 26, 43-48.

Sukumaran, K.K., Neelakandan, B., 1997b. Age and growth in two marine portunid crabs, *Portunus* (Portunus) *sanguinolentus* (Herbst) and *Portunus* (Portunus) *pelagicus* (Linnaeus) along the south-west coast of India. Indian Journal of Fisheries, 44, 111-131.

Sumpton, W.D., Smith, G.S., Potter, M.A., 1989. Notes on the biology of the portunid crab *Portunus sanguinolentus* (Herbst) in subtropical Queensland waters. Australian Journal of Marine and Freshwater Research, 40, 711-717.

15 Species composition, spatial distribution, relative abundance and reproductive biology of mantis shrimps in Moreton Bay, Queensland

J. Taylor and J. A. Haddy

15.1 ABSTRACT

This chapter describes the species composition, spatial distribution, relative abundance and reproductive biology of mantis shrimps in Moreton Bay, Queensland. Eight different species of mantis shrimp were identified from trawl samples. Seasonal trends in the mean monthly reported landings indicated that higher catches were taken during the summer and autumn with catches decreasing to their lowest levels in winter. Timing/seasonality of spawning, size at maturity, sex ratios and morphological data are also discussed for *Oratosquilla stephensoni* and *O. interrupta.* The most abundant species sampled was *O. stephensoni,* which exhibited multi-modal length frequency distributions, suggesting the presence of multiple age cohorts. Seasonal reproductive data indicated that *O. stephensoni* and *O. interrupta* have an annual reproductive cycle with peak spawning from spring to summer. Changes in the frequency of mature *O. stephensoni* and *O. interrupta* and seasonal variations in GSI values suggested that these species may spawn at least twice during the spawning period. The length at first maturity for *O. stephensoni* and *O. interrupta* was 24 mm CL and 28 mm CL respectively. These results are discussed in relation to comparisons between species and other stomatopods, and provide invaluable biological information for assessing the sustainability of current exploitation rates of mantis shrimps within Moreton Bay.

15.2 INTRODUCTION

The order Stomatopoda is a group of at least 450 marine predatory crustaceans, commonly known as mantis shrimps. They have received their common name from the presence of large and powerful raptorial appendages, which they use to “spear” or “smash” prey (Ahyong, 2001; Caldwell and Dingle, 1976). Mantis shrimps are primarily distributed throughout tropical and subtropical waters, where they inhabit burrows or crevices within the intertidal and subtidal zones (Ahyong, 2001). Several species are commercially exploited throughout the world with the most important fisheries being for *Squilla mantis* (Linnaeus, 1758) in the Mediterranean, *Oratosquilla oratoria* (de Haan, 1844) in Japan, and *Oratosquilla nepa* (Latreille in India (Ahyong, 2001; James and Thirumilu, 1993; Maynou et al., 2005). They are normally captured during benthic trawl operations and used as a dependable source of raw material in fishmeal, poultry feeds and fertilisers. However, in some countries they are also eaten as the meat is reported to possess medicinal properties (James and Thirumilu, 1993).

A recent review by Ahyong (2001) reported that 146 species within 63 genera inhabit Australian waters, with 99 of these species being reported from Queensland (Haddy, 2000; Ahyong, 2001). In Australia, mantis shrimps have traditionally been a minor bycatch species caught in commercial prawn trawl fisheries (Dell and Sumpton, 1999). However, Queensland *Fisheries (East Coast Trawl) Management Plan 1999,* which was implemented in 2000, lists mantis shrimps as “permitted species”, thus allowing them to be retained by trawl fishers and marketed. In 2000 the total reported catch of mantis shrimp was three tonnes with an estimated value of A$9000. The majority of this catch is landed from the Moreton Bay area (QLD Fisheries Service, 2001) and sold into domestic Asian markets.

An objective of the Managment Plan is to ensure fisheries’ resources taken in the fishery are harvested in an ecologically sustainable way (QLD DPIF, 1999). In 2004 a productivity susceptibility assessment analysis on mantis shrimps in the Queensland East Coast Trawl Fishery concluded that mantis shrimps had a low capacity to recover from population depletion and a high susceptibility to mortality from trawling (QLD DPIF, 2004). This result was due to the fact that very little reliable data was available on the population dynamics and preferred habitats of Queensland’s exploited mantis shrimp species (QLD DPIF, 2004). Consequently, there is a need to obtain more information on the population dynamics of Queensland's mantis shrimp species in order to correctly assess the sustainability of their exploitation in the QECTF. Size at maturity, seasonality of reproduction, spawning sites, growth and spatial distribution are some of the most important life history parameters needed for stock assessment and management of sustainable exploitation levels. However, to date this information is yet to be investigated in Australian species (QLD Fisheries Service, 2001). Therefore the aim of the study was to describe the species composition and population dynamics of commercially important mantis shrimp species within the Moreton Bay region.

15.3 MATERIALS AND METHODS

15.3.1 Sample collection and processing

Monthly mantis shrimp samples were obtained from commercial prawn trawl fishers operating in Moreton Bay (27°30’ S) between October 2001 and January 2003. Additional samples were also collected during two fishery-independent research trawl surveys in Moreton Bay in November 2001 and again in November 2002 (Ovenden et al., 2004). The Moreton Bay area was divided into five 6-inch x 6-inch logbook grids (grids 7, 12, 13, 14 and 18). Each grid was allocated between 13 and 27 one-nautical mile transects. Grids with a reduced trawlable area received proportionally less sampling effort. The trawl gear consisted of a 5 m beam trawl fitted with a Florida Flyer net composed of 38 mm mesh (Ovenden et al., 2004).

Individual mantis shrimps in samples were identified to species, and total length, carapace length, total weight, sex, presence of stored sperm in the thoracic segments, ovarian maturity and ovarian weight recorded. Total length (TL) was measured from the apex of the rostral plate to the apices of the submedian teeth of the telson, and carapace length (CL) from the median posterior edge of the carapace to the apex of the rostral plate. Criteria for ovarian maturity and macroscopic descriptions are detailed in Table 15.3.1. The presence of stored sperm could only be determined in fresh specimens; therefore as the survey samples were frozen prior to processing, this data could not be determined for these months.

Table 15.3.1. Macroscopic descriptions of ovarian development in mantis shrimp

Stage	Macroscopic Description
1) Undeveloped	Gonad not visible externally. Gonad small with clear or slightly creamy to rose appearance*.
2) Maturing	Gonad visible as small strip on ventral telson. Gonad enlarging with yellow/orange or red colour*.
3) Mature	Gonad visible as a triangle on ventral telson. Gonad enlarged greatly and bright yellow, orange or red colour*.

*ovarian colour varies between species.

15.3.2 Data analysis

All data were pooled for determination of carapace length–total weight (CL–TW) relationships for males and females of six of the eight species (two species, *C. granti* and *O. cultrifer,* had insufficient sample sizes). The cubic relationship between CL and TW was represented by the power curve equation: $TW = a\mathrm{CL}^b$, where b is close to 3 in isometric growth, and a is a constant determined empirically (King, 1995).

Data from the Moreton Bay trawl surveys were used to determine the species composition and spatial distributions of mantis shrimps by individual numbers and total catch weight for both the 2001 and 2002 surveys. However, due to low catch numbers, spatial information is only presented for the four most common species: *O. stephensoni, O. interrupta, B. laevis* and *A. fasciata*.

Oratosquilla stephensoni was the only species sampled in sufficient numbers to produce robust monthly length-frequency distributions for both males and females required to determine von Bertalanffy growth parameters. Estimates of L_∞ were determined by averaging the ten largest individual carapace lengths recorded for each sex, and the parameters k and t_0 determined by using a von Bertalanffy plot (relative age against $-ln(1-L_t/L_\infty)$) (King, 1995). Data obtained for this method were determined from modal peaks present in monthly length-frequency distributions of males and females, respectively.

Gonadosomatic indices (GSI) were calculated as gonad weight/total weight x 100. Seasonal GSI profiles were generated from individuals larger than 20.5 mm CL to ensure that immature values did not bias seasonal mean GSI values (Haddy et al., 2005). Mandatory logbook data for mantis shrimps from 2000–2005 were used to examine spatial and temporal trends in reported landings.

15.4 RESULTS

15.4.1 Analysis of logbook data

Total reported annual landings of mantis shrimps from 2000 to 2005 were 2425, 651, 723, 1369, 1251 and 654 kg, respectively, with the great majority of the catch (i.e., 96%) reported from Moreton Bay (Figure 15.4.1). Catches were lowest in winter (June, July and August) and peaked between late summer and early autumn (February to April).

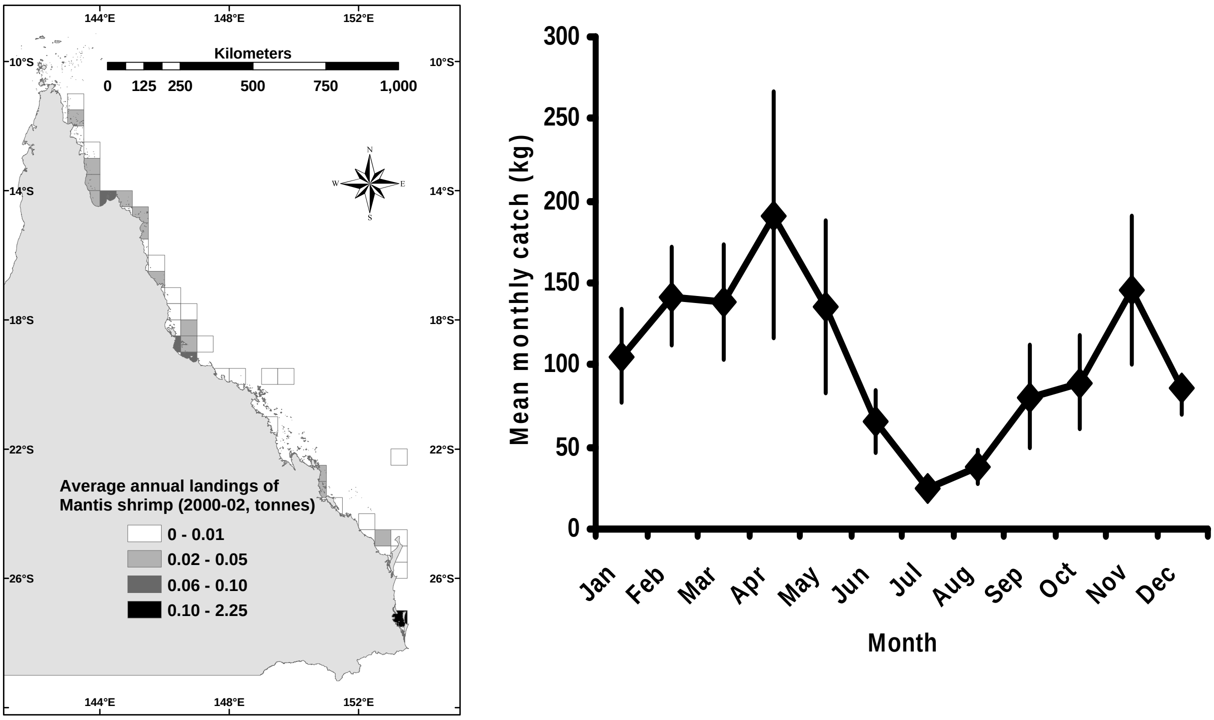


Figure 15.4.1. Spatial and temporal trends of reported mantis shrimp landings from the Queensland East Coast Trawl Fishery

15.4.2 Sample details

A total of 3809 mantis shrimps were collected with eight species being recorded. Combined sample details and morphometric measurements for all species are provided in Table 15.4.1 and Table 15.4.2, respectively. With all samples pooled, *Oratosquilla stephensoni* was the most abundant species, followed by *O. interrupta*, *Belosquilla laevis*, *Erugosquilla woodmasoni*, *Anchisquilla fasciata* and *Harpiosquilla harpax*, with sample sizes of 583, 237, 204, 130 and 60, respectively. Only two specimens of *Odontodactylida cultrifer* and one specimen of *Clorida granti* were collected. *Harpiosquilla harpax* was the largest mantis shrimp encountered with a maximum size and weight of 252 mm TL and 166 g.

Table 15.4.1. Details of the total numbers of mantis shrimp collected and their minimum, maximum and mean carapace lengths (all data pooled)

Species	Sex	Max TW (g)	Max CL (mm)	Mean CL (mm)	Total Numbers
Anchisquilla fasciata	M	9.2	20.7	15.4	75
	F	7.8	19.4	14.0	55
Belosquilla laevis	M	20.5	27.1	18.8	100
	F	17.0	25.2	18.0	137
Oratosquilla interrupta	M	67.4	43.3	35.6	326
	F	76.6	43.8	35.7	257
Oratosquilla stephensoni	M	49.1	36.6	27.4	1271
	F	58.6	41.3	29	1321
Clorida granti	M				-
	F	2.0	9	9	1
Erugosquilla woodmasoni	M	71.4	38.5	31.3	101
	F	64	39.1	31.9	103
Harpiosquilla harpax	M	165.7	52.1	42.7	30
	F	117.7	57.4	45	30
Odontodactylida cultrifer	M				-
	F	12.5	21.1	19.3	2

Table 15.4.2. Regression parameters for the carapace length-total weight (CL-TW) relationship for six species of mantis shrimp (all data pooled)

Species	Sex	n	$TW = aCL^b$			CL MAX (mm)
			a	b	r^2	
Anchisquilla fasciata	M	75	0.0043	2.7187	0.8392	20.7
	F	55	0.0043	2.4896	0.7872	19.4
Belosquilla laevis	M	100	0.0029	2.6632	0.9299	27.1
	F	137	0.0021	2.7754	0.8804	25.2
Oratosquilla interrupta	M	326	0.0049	2.5299	0.8645	43.3
	F	257	0.0045	2.5551	0.8687	43.8
Oratosquilla stephensoni	M	1271	0.0341	1.9127	0.659	36.3
	F	1321	0.0022	2.7521	0.9446	41.3
*Clorida granti**	M	-	-	-	-	-
	F	1	-	-	-	9
Erugosquilla woodmasoni	M	101	0.0028	2.7386	0.8879	38.5
	F	103	0.0041	2.6313	0.9201	39.1
Harpiosquilla harpax	M	30	0.001	2.9828	0.952	52.1
	F	30	0.0018	2.8378	0.9619	57.4
*Odontodactylida cultrifer**	M	-	-	-	-	
	F	2	-	-	-	21.1

* Note: (-) indicates insufficient data to determine a length-weight relationship

15.4.3 Species composition

The species compositions of the 2001 and 2002 Moreton Bay trawl surveys are shown in Figure 15.4.2. A total of eight species were collected, however *C. granti* was only present in the 2002 survey. The total number of individuals caught in 2001 and 2002 were n = 685 and n = 485, respectively. *Oratosquilla stephensoni* dominated the survey catches and accounted for 50.2% and 72.4% of individuals caught in 2001 and 2002, correspondingly. This species also accounted for 58.8% and 81.0% of the total weight for the 2001 (total catch weight = 11.6 kg) and 2002 (8.4 kg) trawl surveys, respectively. The remaining species in order of numerical abundance from the 2001 and 2002 surveys were as follows: *B. laevis* (24.4 and 13.8%), *A. fasciata* (13.1 and 8.2%), *O. interrupta* (10.4 and 3.7%), *E. woodmasoni* (1.2 and 0.4%), *H. harpax* (0.1 and 0.4%), *O. cultrifer* (0.1 and 0.2%) and *C. granti* (n/a and 0.2%).

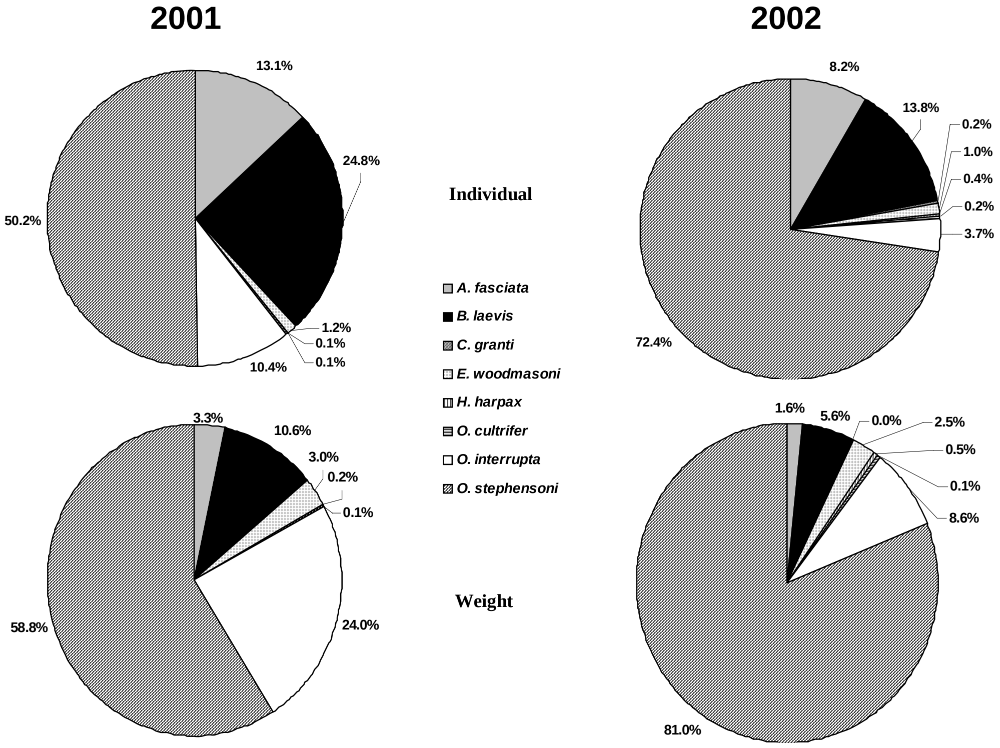


Figure 15.4.2. Proportional catches by individuals and weight of mantis shrimp caught during the 2001 and 2002 Moreton Bay trawl surveys

15.4.4 Species distribution and abundance

Detailed maps of the spatial distribution and relative abundance of the four most common mantis shrimp species, *O. stephensoni*, *B. laevis*, *A. fasciata* and *O. interrupta*, are provided in Figure 15.4.3 through to Figure 15.4.10. In 2001 the highest proportions of *O. stephensoni*, *O. interrupta* and *A. fasciata* were caught in grids 12, 13 and 12, respectively, however in 2002, their abundances were highest in grids 18, 13 and 14, respectively. In contrast *B. laevis* was most abundant in grid 7 for both years. A breakdown of catch rates for each species encountered during the surveys is detailed in Table 15.4.3.

Table 15.4.3. Summaries of mantis shrimp catch rates from Moreton Bay

2001 survey

Species	**n**	**Grid of highest abundance**	**Max catch rate (g ha^{-1})**	**mean catch rate (g ha^{-1})**	**Max catch rate n ha^{-1}**	**mean catch rate n ha^{-1}**
A. fasciata	90	13	65.37	4.86±1.39	18.5	1.16±0.34
B. laevis	170	7	394.48	15.91±7.31	57.4	2.19±1.01
E. woodmasoni	8	14	86.12	4.50±1.98	1.8	0.1±0.04
H. harpax	1	12	19.82	0.28±0.28	0.9	0.01±0.01
O. cultrifer	1	14	10.56	0.15±0.15	0.9	0.01±0.01
O. interrupta	71	13	269.46	35.16±6.09	6.5	0.89±0.14
O. stephensoni	344	12	475.96	86.71±10.20	22.2	4.32±0.54
Combined spp.	685	7	606.99	147.6±15.7	60.1	8.68±1.18
2002 survey						
A. fasciata	40	14	18.71	1.60±0.43	5.56	0.47±0.14
B. laevis	67	7	65.56	5.55±1.37	8.33	0.79±0.17
C. granti	1	7	1.85	0.02±0.02	0.93	0.01±0.01
E. woodmasoni	5	18	59.26	2.53±1.19	0.93	0.06±0.03
H. harpax	2	7	41.58	0.53±0.53	1.85	0.02±0.02
O. cultrifer	1	14	9.35	0.12±0.12	0.93	0.01±0.01
O. interrupta	18	13	95.47	8.52±2.25	1.85	0.21±0.05
O. stephensoni	351	18	376.51	80.37±9.49	18.52	4.11±0.49
Combined spp.	485	14	475.22	99.22±10.89	21.3	5.68±0.54

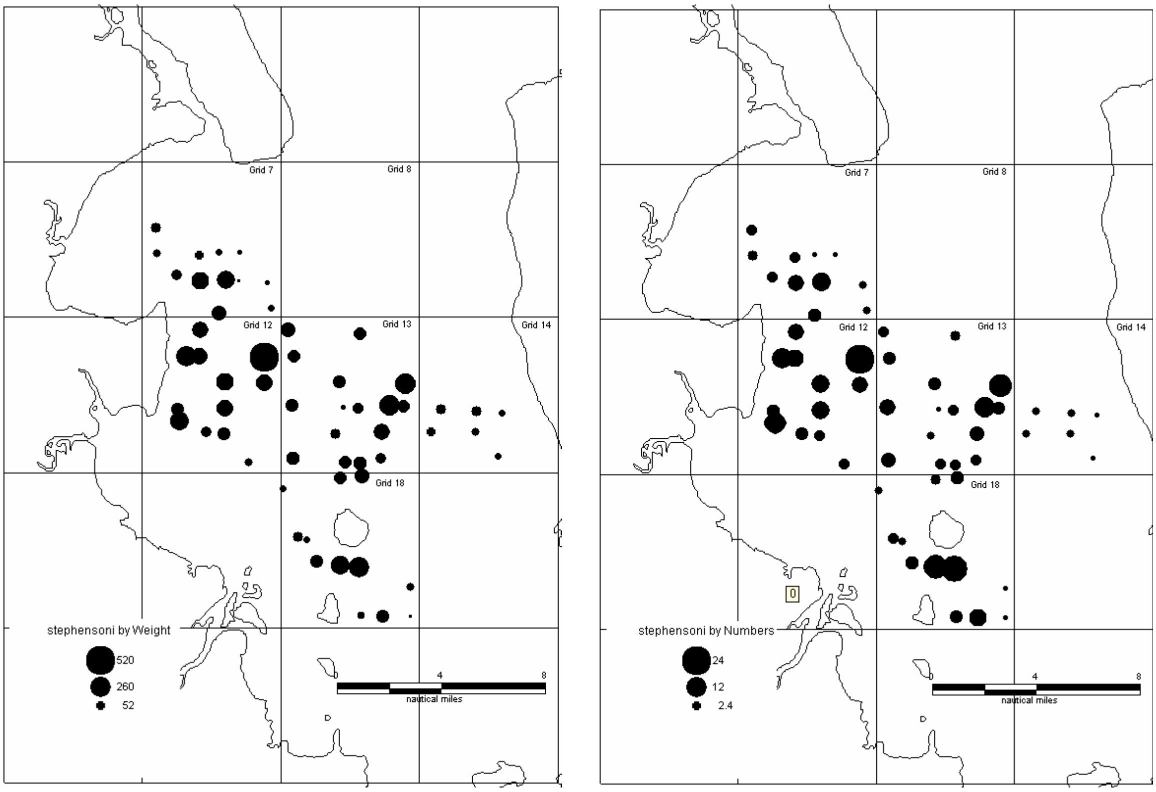


Figure 15.4.3. Spatial distribution and abundance of *O. stephensoni* by weight (g) and number in 2001.

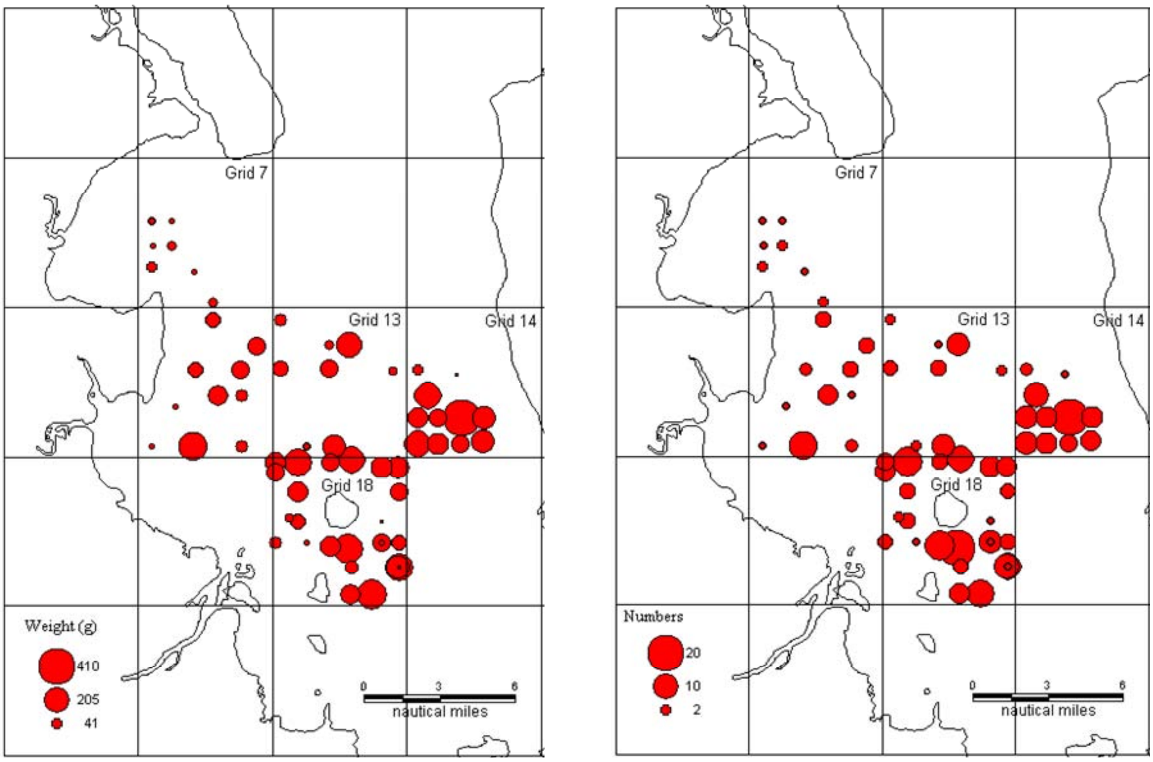


Figure 15.4.4. Spatial distribution and abundance of *O. stephensoni* by weight (g) and number in 2002.

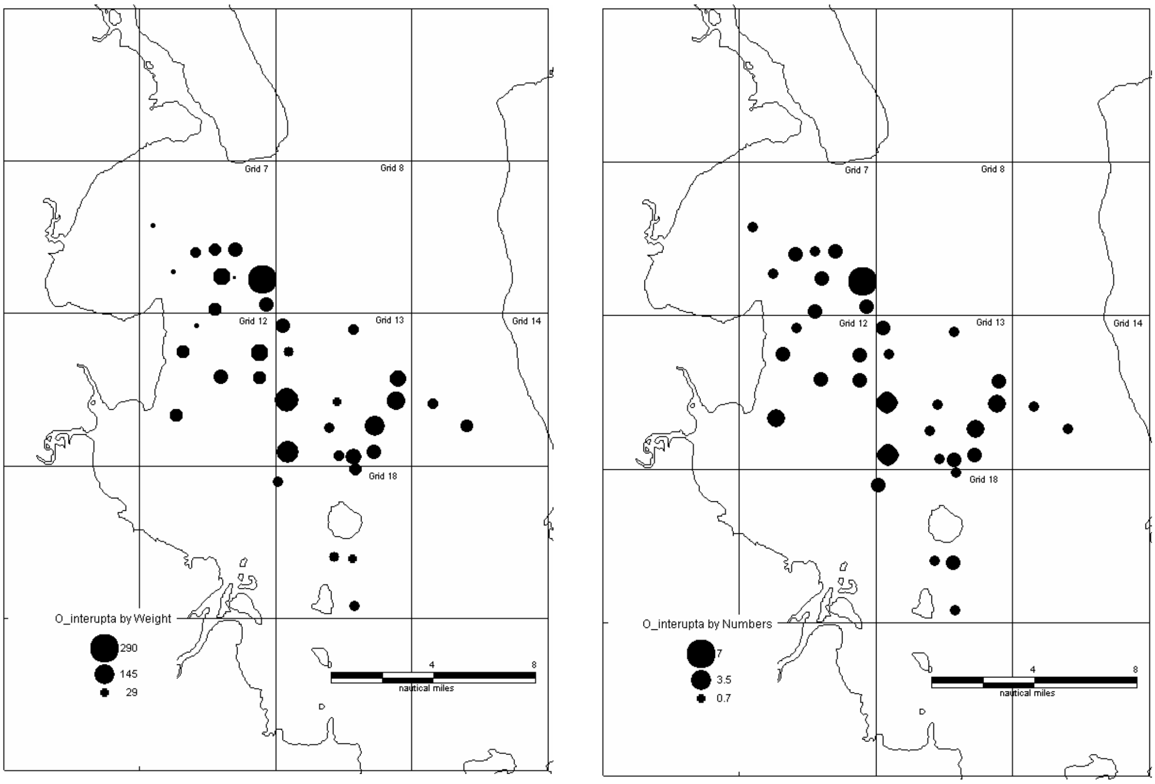


Figure 15.4.5. Spatial distribution and abundance of *O. interrupta* by weight (g) and numbers in 2001.

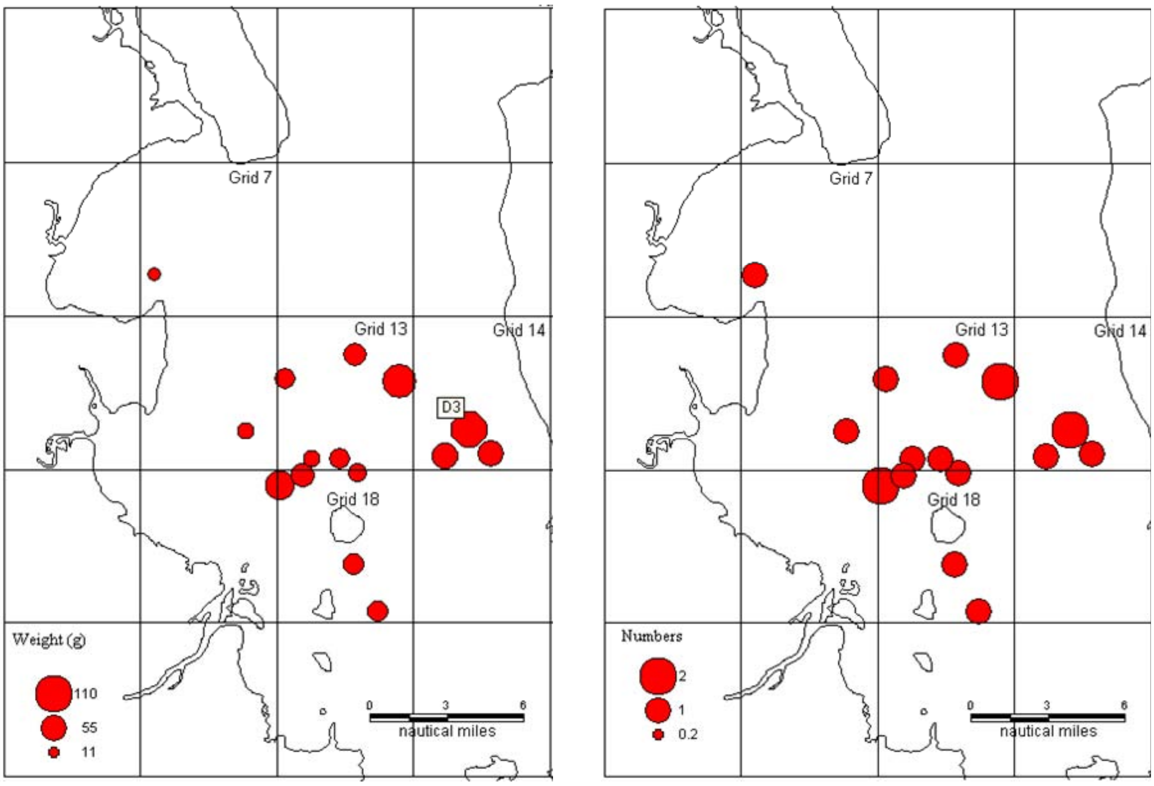


Figure 15.4.6. Spatial distribution and abundance of *O. interrupta* by weight (g) and number in 2002.

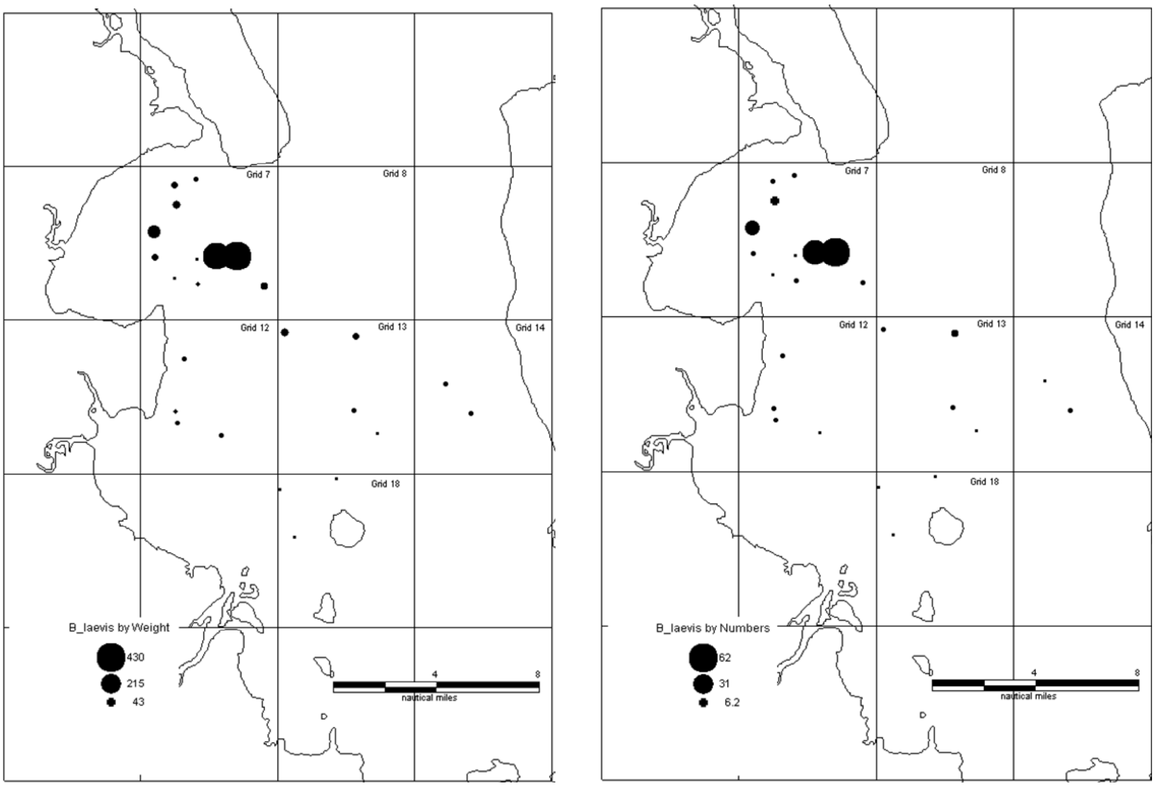


Figure 15.4.7. Spatial distribution and abundance of *B. laevis* by weight (g) and number in 2001.

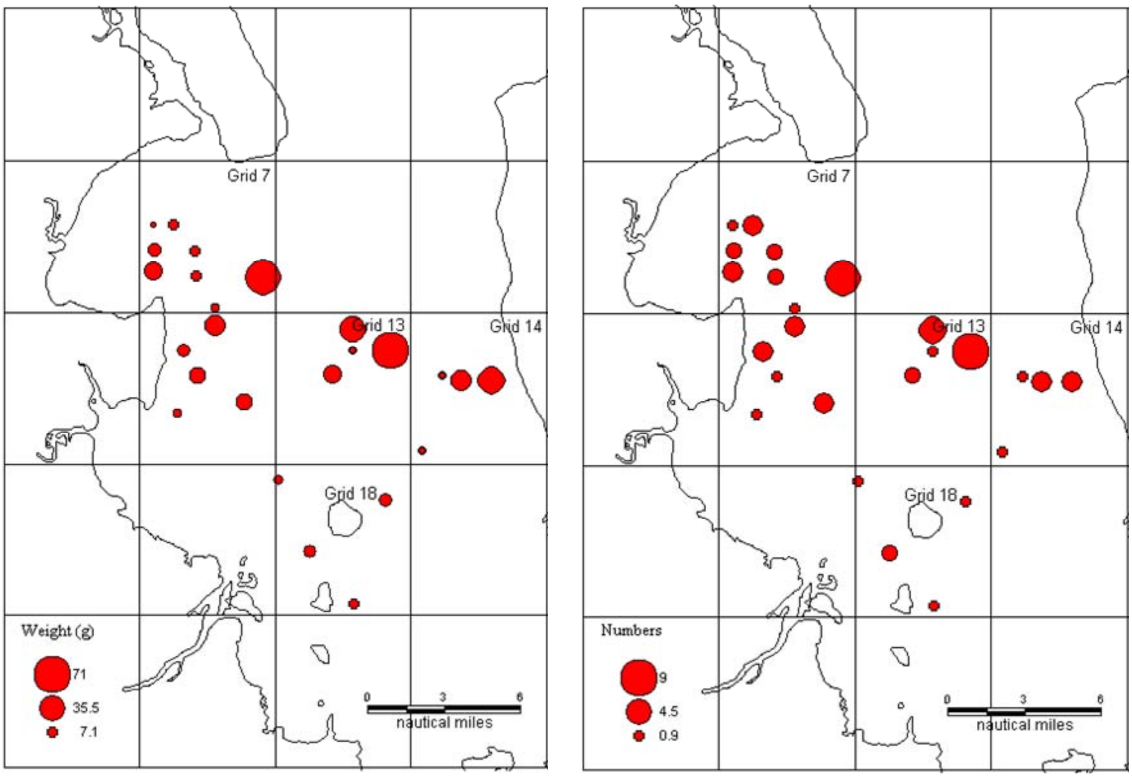


Figure 15.4.8. Spatial distribution and abundance of *B. laevis* by weight (g) and number in 2002.

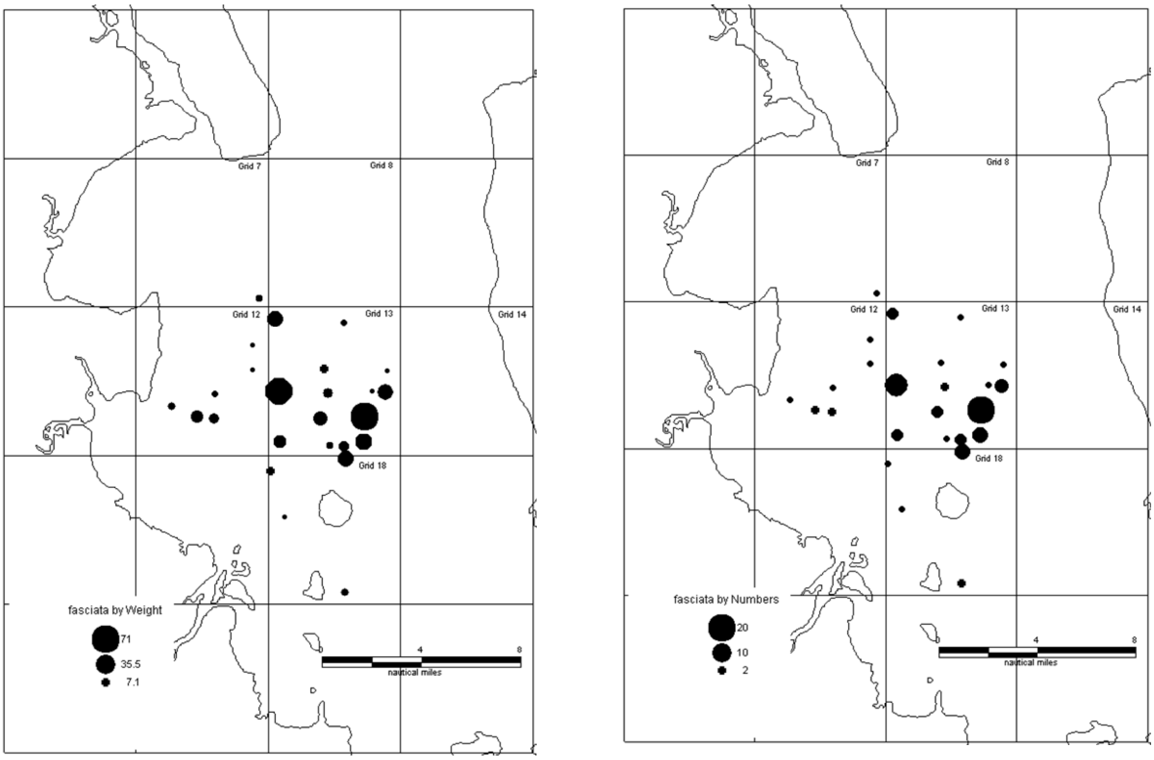


Figure 15.4.9. Spatial distribution and abundance of *A. fasciata* by weight (g) and number in 2001.

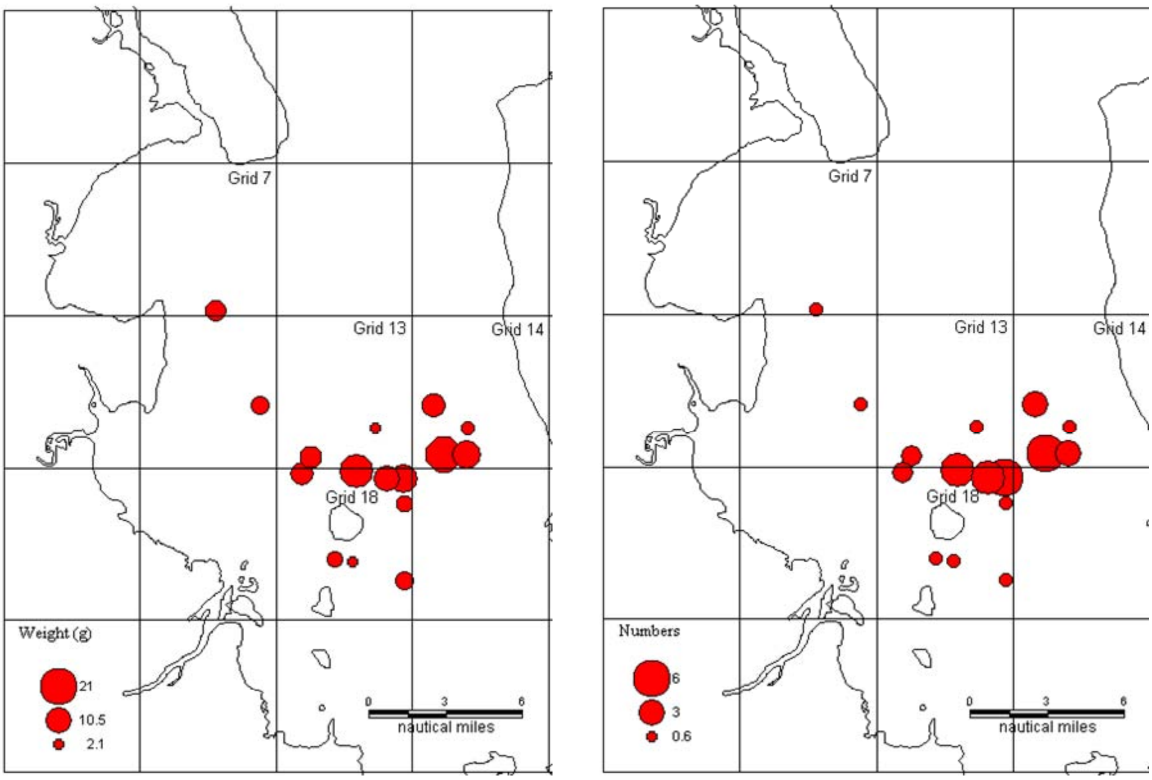


Figure 15.4.10. Spatial distribution and abundance of *A. fasciata* by weight (g) and number in 2002.

15.4.5 *Monthly length-frequency distributions and growth of* Oratosquilla stephensoni

Oratosquilla stephensoni was the only species sampled in sufficient numbers to derive von Bertalanffy growth parameters. Carapace lengths ranged from 15.4 mm to 41.3 mm CL with length-frequency distributions being either unimodal or multimodal, depending on the month of collection (Figure 15.4.11 and Figure 15.4.12). Multi-modal distributions were most evident in November 2001 and August to November 2002. These additional modes were present due to the capture of smaller sized individuals (14 mm to 20 mm CL) in these months. Estimates of L_∞, k and t_0 were 35.5 mm CL, 1.69 and 0.5 for males, and 38.9 mm CL, 1.40 and 0.49 for females, respectively. Growth curves suggested a life span of approximately 2.5 to 3 years.

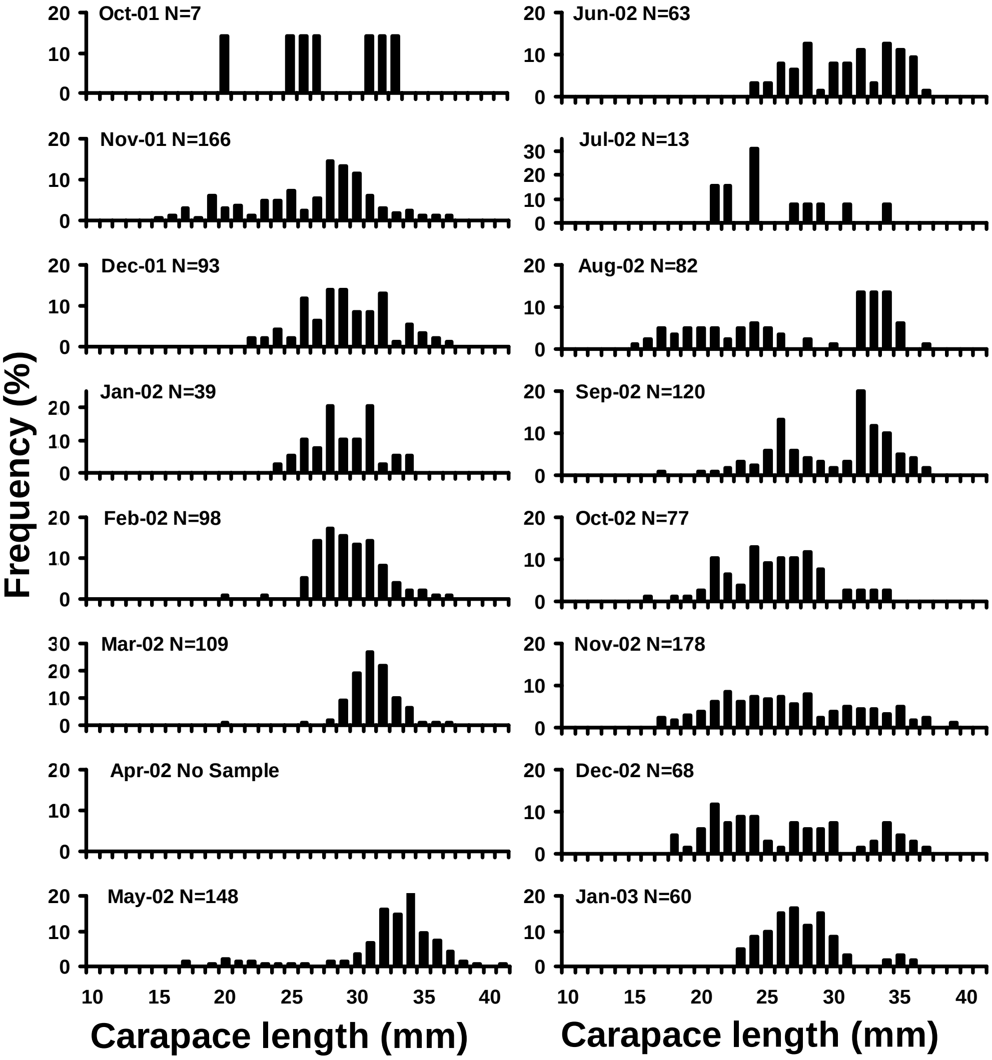


Figure 15.4.11. Monthly carapace length-frequency distributions of female *Oratosquilla stephensoni* (all data pooled). Note: y-axis ranges vary.

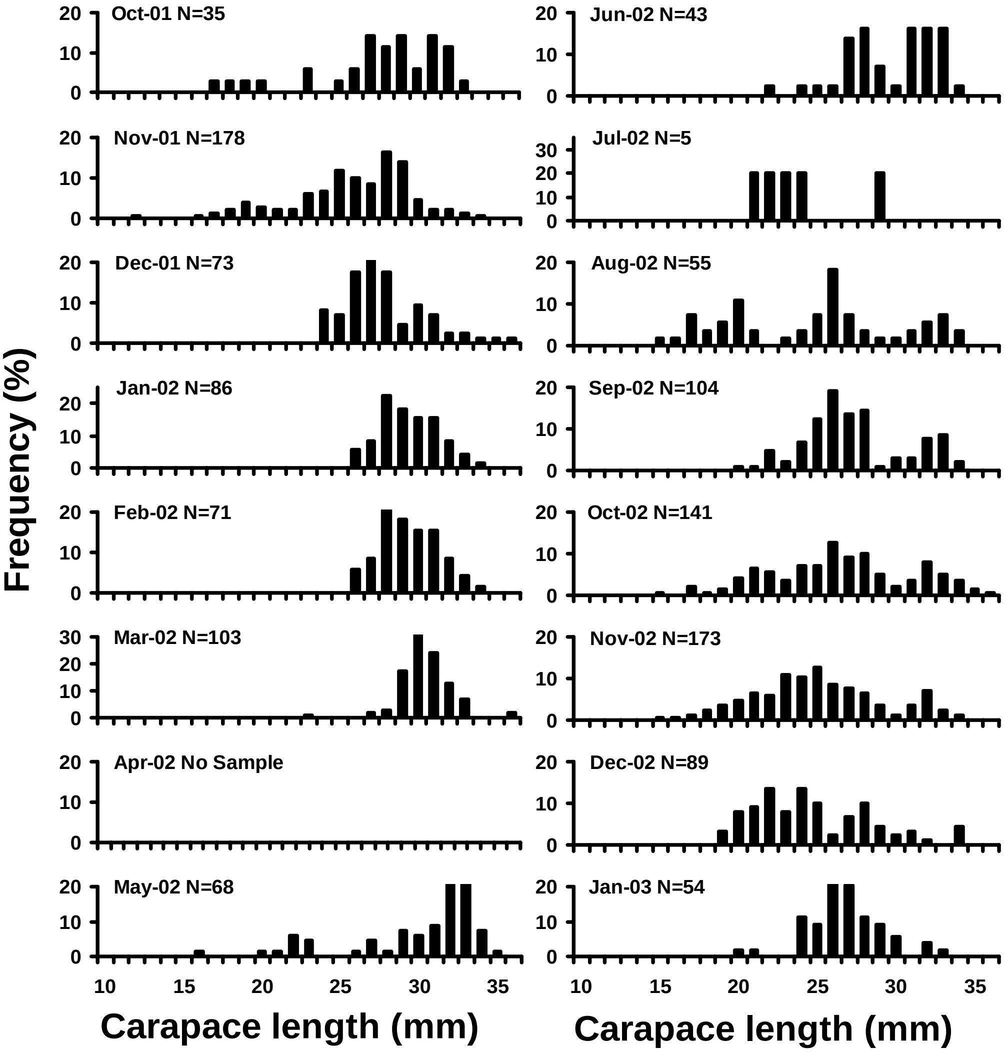


Figure 15.4.12. Monthly carapace length-frequency distributions for male *Oratosquilla stephensoni* (all data pooled). Note: y-axis ranges vary.

15.4.6 Reproductive activity of female Oratosquilla stephensoni

The GSI profile of *O. stephensoni* displayed a clear annual cycle, with values being initially high in October 2001 before declining to their lowest values between March and July 2002. GSI values then rapidly increased to maximum levels between September and November 2002 (Figure 15.4.13). A small secondary peak was also evident in January 2002. Seasonal sex ratios of females to males were at their lowest (< 40%) during October 2001, January 2002 and October 2002. The proportions of mated females were highest (> 50%) in October 2001, August 2002 and September 2002 and were at their lowest in December 2001, May 2002 and July 2002. The proportions of reproductively active *O. stephensoni* displayed a clear seasonality, with maturing and mature stage females abundant over spring and summer. In contrast, inactive females with undeveloped (stage 1) gonads predominated over autumn and winter (Figure 15.4.13). The smallest sexually mature individual measured 20.4 mm CL with 50% size at maturity being reached at 24.0 mm CL.

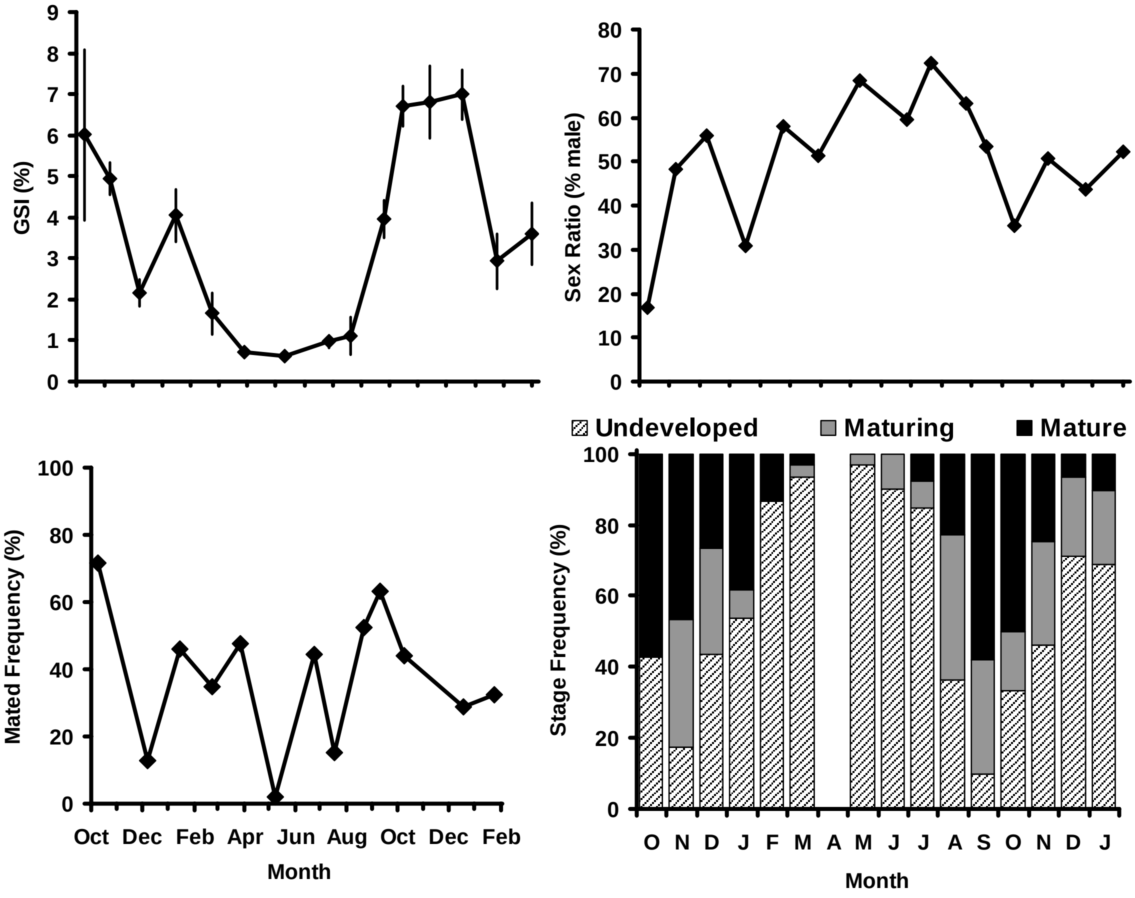


Figure 15.4.13. Seasonal changes in gonadosomatic indices (GSI), sex ratio, mated frequency and ovarian development for female *Oratosquilla stephensoni*

15.4.7 Reproductive activity of female Oratosquilla interrupta

Seasonal reproductive trends in *O. interrupta* displayed a clear cycle similar to that of *O. stephensoni* (Figure 15.4.14). The results highlighted that reproductive activity was highest in spring and summer with high GSI values and the proportions of fully mature individuals abundant at these times. A secondary peak of reproductive activity also occurred in January 2002. The female sex ratio was associated with these peak reproductive events as female presence was lowest during the months of October 2001, January 2002 and October 2002. The presence of mated females was typically high throughout the year except during winter (May–July) when the incidence of mated females was extremely low. The smallest sexually mature individual measured 27.5 mm CL with 50% size at maturity being reached at 28.0 mm CL.

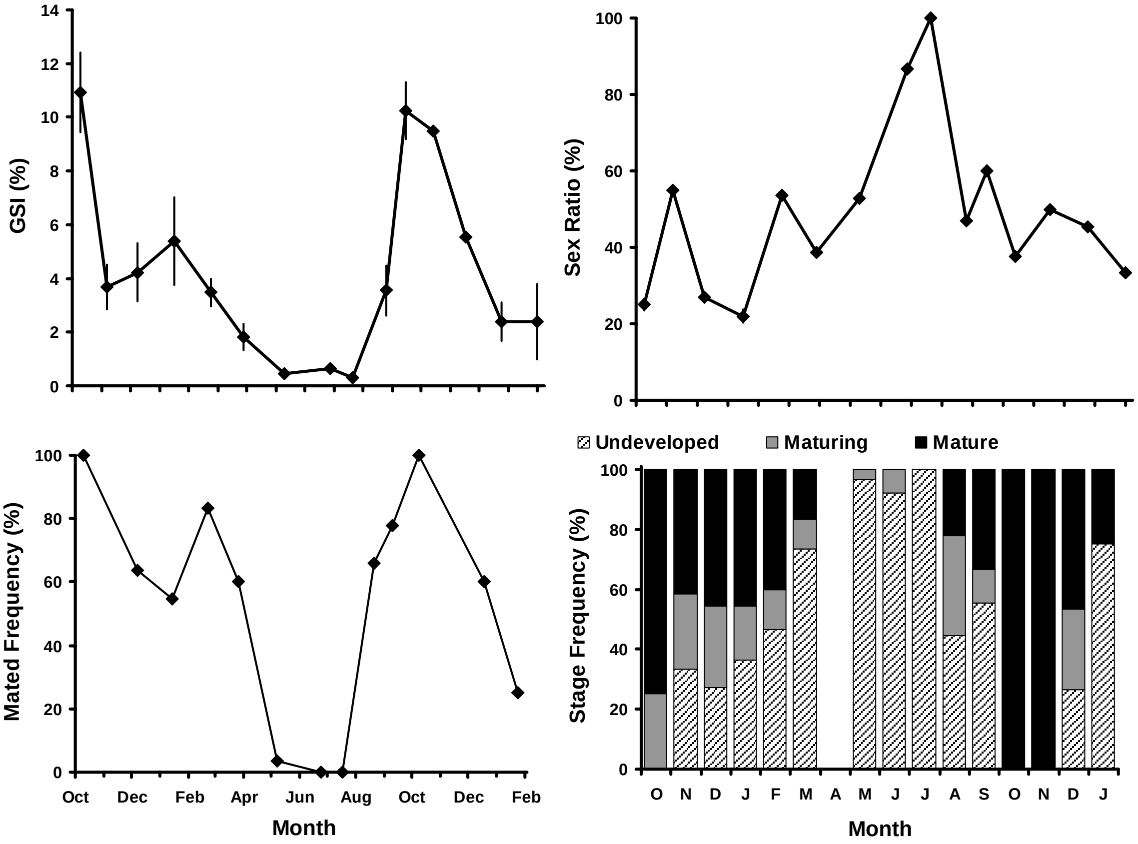


Figure 15.4.14. Seasonal changes in gonadosomatic indices (GSI), sex ratio, mated frequency and ovarian development for female *Oratosquilla interrupta*

15.5 DISCUSSION

A total of eight species of mantis shrimp were caught in the Moreton Bay region using commercial prawn trawl nets during the sampling period. Seven of the species – *A. fasciata, B. laevis, E. woodmasoni, H. harpax, O. cultrifer, O. interrupta* and *O. stephensoni* – are known to be harvested and marketed by fishers within the Moreton Bay Otter Trawl Fishery (MBOTF) (Dell and Sumpton, 1999; Haddy, 2000). *O. stephensoni* was the most abundant species during the sampling period; it was also the most common species caught during a similar study in this area by Dell and Sumpton (1999). The reported mean monthly landings of mantis shrimps varied seasonally with the greatest catch rates occurring during summer and autumn before declining during winter. Similarly Dell and Sumpton (1999) observed greater abundances of *O. stephensoni, O. interrupta, A. fasciata* and *B. laevis* in Moreton Bay over summer and dramatically decreased catch rates during winter. Giovanardi and Piccinetti-Manfrin (1984), and Froglia (1996) (in Maynou et al., 2005), from studies of *Squilla mantis* in the Adriatic and Mediterranean seas, concluded that decreased catch rates resulted from reduced female out-of-burrow activity when incubating their eggs and disappearance from the population of adults after spawning. Maynou et al. (2005)

suggested that the seasonal differences in catch rates of *S. mantis* in the Mediterranean were due to the dynamics of the exploited stock, not a seasonal relocation of effort. Maynou et al. (2005) went on to explain that the seasonal variation in the population structure was consistent with the addition of recruits (winter–spring) and the disappearance of adults (summer–autumn).

The spatial distribution and abundance of *O. stephensoni* and *A. fasciata* varied between the two sampling years of the Moreton Bay survey. However, catches of these species occurred in Grid 13 each year. Dell and Sumpton (1999) observed the area of grid 13 as being the deepest station (station 5) in their study and also with higher densities of different species in this area. The fact that *B. laevis* was mostly abundant in grid 7 for both years is consistent with the findings of Ayhong (2001), who suggested that the preferred habitat of this species was intertidal areas to 40 m that were often associated with seagrass beds, which is typical of the grid 7 area. The variations in distribution and abundance may also be the result of seasonal differences in rainfall over the sampling period. This relates to the findings of Froglia (1996) in Maynou et al. (2005) who found the high densities of mantis shrimps in areas of the Adriatic that experienced high levels of river run-off.

The monthly length-frequency distributions of *O. stephensoni* (male and female) displayed multimodal distributions indicating the presence of multiple cohorts up to three years of age. Similarly length-frequency analysis of *O. stephensoni* in Moreton Bay by Dell and Sumpton (1999) reported the species to have a life span of approximately 2.5 years and suggested two distinct periods of spawning and recruitment. Furthermore, Dell and Sumpton (1999) stated that the presence of the two cohorts together with multiple spawning events, fast growth and short-lived population dynamics of *O. stephensoni* would imply a high turnover of stock. Although two recruitment periods were not detected in the present study, the seasonal GSI profiles and ovarian maturity indicated that two spawning events were likely to occur during the reproductive season. In a study of the population dynamics of *Oratosquilla nepa* (Latreille) of the Mangalore Coast, Reddy and Shanbhogue (1994) determined that the fishery was exclusively supported by smaller size groups every November. This indicated bulk recruitment into the fishery around this period. A further recruitment of smaller size groups in May suggested that this species spawned twice a year (Reddy and Shanbhogue, 1994).

Seasonal changes in the proportions of female to male sex ratios, GSI, mated frequency, and ovarian stage of development indicate that *O. stephensoni* and *O. interrupta* displayed an annual cycle of reproduction. Peak spawning is observed to be during spring with a likely secondary spawning period during late summer. Populations of mantis shrimp are known to breed for extended periods often with peaks in frequency in tropical waters (Haddy, 2000). Reddy and Shanbhogue (1994) found *Oratosquilla nepa* of the Mangalore Coast to have an extended spawning period of 10 months with peaks in February to April and September to October. The decreased female to male sex ratios for both species observed during late summer to early autumn and spring of the sampling period suggest that females may be in their burrows incubating their eggs, which is consistent with the spawning periods from the GSI analysis mentioned earlier. Maynou et al. (2005) found *S. mantis* in the Mediterranean to incubate their eggs during summer and spring and not leave the burrow throughout this incubation period. Maynou et al. (2005) concluded that the reproductive behaviour of *S. mantis* influences the proportion of males and females in catches by season – females outnumber males only during the mating season. The high proportions of mated frequency in spring and late summer show a relationship with the frequency of mature and maturing individuals caught. This relationship suggests a mating season in spring to late summer. The high abundance of undeveloped females during autumn and winter correlates with the low GSIs over the same period, which is consistent with the suggestion of a spawning season over this period.

During this study we were able to determine an approximation of size at maturity for female *O. stephensoni* and *O. interrupta.* By inspecting the ovaries and assigning a reproductive stage to each individual, the size at maturity was established from the minimum CL of the mature (stage 2 and 3) females. The size at maturity for *O. interrupta* and *O. stephensoni* was 28 mm CL and 24mm CL, respectively. Maynou et al. (2005) determined a similar size at maturity for female *S. mantis* in the Mediterranean as 20–24 mm CL.

The results provide fishers and fisheries managers with detailed information on the spatial distribution, abundance, species composition and reproductive biology of commercially caught mantis shrimp species in Moreton Bay. While significant catches of mantis shrimp are caught incidentally throughout the East Coast Trawl Fishery (see the Appendices listing bycatch composition in the various sectors), their retention and marketing are largely limited to the Moreton Bay fleet, probably for socio-economic reasons. Based on discussions with fishers, most crews operating outside Moreton Bay are not motivated to retain mantis shrimp. A key component of the study was to provide fisheries managers with information on the population dynamics of mantis shrimps so informed management decisions could be made. The findings highlighted concerns that the current commercial trawl methods are landing immature mantis shrimps. However, as the mantis shrimps studied a) display a relatively fast growth rate with a short life span, b) possess a prolonged spawning season with at least two spawnings per season, c) have a cryptic lifestyle where females remain in their burrows during the egg mass incubation period, and d) are retained almost solely by the Moreton Bay fleet, it is likely that current exploitation rates are within sustainable limits.

15.6 REFERENCES

Ayhong, S.T., 2001. Revision of the Australian Stomatopoda Crustacea. Records of the Australian Museum. Supplement 26, pp. 1-326.

Cadwell, R.L., Dingle, H., 1976. Stomatopods. Scientific American, Vol. 19, no. 1, pp. 126-133.

Dell, Q., Sumpton, W., 1999. Stomatopod Bycatch from Prawn Trawling in Moreton Bay". Asian Fisheries Science, Vol. 12, pp. 133-144.

Haddy, J., 2000. Literature Review: The biology and population dynamics of permitted fish species in the Queensland East Coast Trawl Fishery. Department of Primary Industries. unpub.

Haddy, J.A., Anthony, J., Courtney, T., Darren, P.R., 2005. Aspects of the Reproductive Biology and Growth of Balmain bugs (*Ibacus* spp.) (Scyllaridae). Journal of Crustacean Biology, Vol. 25, no.2, pp. 263-273.

James, D.B., Thirumilu, P., 1993. Population Dynamics of *Oratosquilla nepa* in the Trawling Grounds off Madras. Journal of Biological Assessment. India. Vol. 35 (1 & 2), pp. 135-140.

Jennings, S., Kaiser, M.J., Reynolds, J.D., 2001. Marine Fisheries Ecology. Blackwell Science Ltd. Oxford, London.

King, M., 1995. Fisheries Biology, Assessment and Management. Fishing News Books. Blackwell Science Ltd, UK.

Maynou, F., Abello, P., Sartor, P., 2005. A Review of the Fisheries Biology of the Mantis Shrimp, *Squilla mantis* (L.1758) (Stomatopoda, Squillidae) in the Mediterranean. Crustaceana, Vol. 77, no. 9, pp. 1081-99.

Ovenden, J.R., Street, R., Peel, D., Peel, S.L., Courtney, A.J., Podlich, H.M., Basford, K.E., Dichmont, C.M., 2004. A new data source for fisheries resource assessment: Genetic estimates of the effective number of spawners. Department of Primary Industries and Fisheries, Brisbane, Australia.

QLD DPIF, 1999. Fisheries (East Coast Trawl) Management Plan 1999. Department of Primary Industries and Fisheries. Brisbane, Australia.

QLD Fisheries Service. 2001. “Plan Review Paper permitted fish (other than principal fish) and steaming day review”, Fisheries (East Coast Trawl) Management Plan 1999, Information Series no. Q101055. Queensland Fisheries Service, Department of Primary Industries. Brisbane, Australia.

QLD Fisheries Service, 2004. Review of the sustainability of fishing effort in the Queensland East Coast Trawl Fishery, ECTF General Review 2004. Department of Primary Industries and Fisheries. Brisbane, Australia.

Reddy, H.R.V., Shanbhogue, S.L., 1994. The Reproductive Biology of the Mantis Shrimp, *Oratosquilla nepa* (Latreille) from Mangalore, Mahasagar, Vol. 27, no. 1 (June), pp. 67-72.

Williams, L.E. (ed.), 2002. Queensland’s Fisheries Resources: Current condition and recent trends 1988–2000. QI02012. Department of Primary Industries and Fisheries, Brisbane, Australia.

16 Exploring associations between pipehorse (*Solegnathus* cf. *hardwickii*) abundance and bycatch faunal communities in the Queensland trawl fishery

A. J. Courtney, M. L. Tonks, D. P. Roy, J. A. Haddy, E. Jebreen and M. J. Campbell

16.1 ABSTRACT

This chapter presents results from an exploratory study of associations between pipehorses, *Solegnathus* cf. *hardwickii* and other species in the Queensland East Coast Trawl Fishery bycatch. Since there is very little known about the habitat requirements of *S.* cf. *hardwickii* the intention of the study was to identify the types of faunal communities that pipehorses may be associated with, and eventually infer information about their habitats based on these associations. Associations were investigated for pipehorses in the scallop fishery and the shallow water eastern king prawn fishery. Information on catch rates of *S.* cf. *hardwickii* and other bycatch species were obtained from research surveys and charters undertaken in both sectors. Exploring the influence of abiotic factors on the bycatch community structure was limited to sample site latitude and depth, and the type of bycatch reduction device (BRD) in the nets. Multidimensional scaling (MDS) indicated that the bycatch composition in both sectors could be grouped using depth as a category. Depth groupings showed greater dissimilarity in the eastern king prawn bycatch (stress = 0.16) compared to the scallop bycatch data (stress = 0.20). *S.* cf. *hardwickii* was associated with 30 m and 40 m groupings in the scallop fishery and an 80 m group in the eastern king prawn fishery. Pipehorses from the eastern king prawn fishery were much smaller those from the scallop fishery and elsewhere along the Queensland coast. Species that accounted for within-group similarity of the 30 m, 40 m, and 80 m groups and whose catch rates were positively correlated with *S.* cf. *hardwickii* were concluded to be species most likely to associate with pipehorses. In the scallop fishing grounds these species were the green puller *Pristosis jerdoni,* the cardinal fish *Apogon poecilopterus,* the bar-faced weaver *Parapercis nebulosa,* the blue-tailed whiptail *Pentapodus paradiseus* and high-finned dragonet *Synchiropus rameus.* The cardinal fish *Apogon brevicaudatus* and an unidentified ascidian were also positively correlated with pipehorse catch rates but did not contribute significantly to the 30 m and 40 m group similarity. In the shallow water eastern king prawn fishing grounds species that accounted for most of the similarity in the 80 m group and were positively correlated with *S.* cf. *hardwickii* were the orange-freckled flathead *Ratabulus diversidens,* the violet roughy *Optivus* sp. *1*, the threadfin bream *Nemipterus theodorei* and goatfish *Upeneus tragula*. In general, there were more significant correlations (both negative and positive) with *S.* cf. *hardwickii* in the king prawn bycatch data. Species that had negative correlations that also contributed to the 80 m group similarity were the grinner *Saurida grandisquamis* and the flathead *Platycephalus longispinis* – both with correlation coefficients of –0.25. Other species in the king prawn bycatch that were not found to contribute significantly to the 80 m group similarity but did have significant positive correlations with *S.* cf. *hardwickii* were the goosefish *Lophiomus setigerus* (correlation coefficient of 0.58) and grinner *Saurida filamentosa* (correlation coefficient of 0.48).

16.2 INTRODUCTION

Little is known about the habitat requirements of pipehorses *Solegnathus* spp. or abiotic factors affecting their distribution. While catches have been confirmed from locations distributed along much of the Queensland coast, most of the trade in pipehorses is based on catches between Townsville (19^{o}30' S) and Caloundra (27^{o} S).

The most detailed information reported to date on pipehorse catch rates and distribution in Queensland thus far has been obtained from the annual Queensland Fishery Service (QFS) Long-Term Monitoring fishery-independent surveys in the Central Queensland scallop fishing grounds (see Connolly et al., 2001). Based on the 1999 and 2000 surveys, there was evidence to suggest that catch rates of *S.* cf. *hardwickii* were positively correlated with the carbonate fraction of the sediments and that pipehorses were generally restricted to depths greater than 27 m, although the maximum depth that they are found in remains uncertain. The 2000 Long-Term Monitoring scallop fishery-independent survey also collected bycatch samples from a subset of the trawls it conducted.

Information on the distribution and catch rates of pipehorses has also been collected during the research charters and opportunistic sampling conducted in the current project. Although information on the abiotic factors affecting the distribution of pipehorses may be scant, the bycatch samples obtained from the 2000 Long-Term Monitoring scallop fishery-independent survey and the current project may provide information on the faunal communities that pipehorses are associated with. It may eventually be possible to infer a description of the habitat for pipehorses, based on the species they occur with or form associations with.

To this end, this chapter investigated the faunal community structure of the trawl bycatch and its relationship to the distribution of pipehorses. The investigation is exploratory and any inferences should be interpreted with caution. Trawl catch rates of pipehorses are relatively low and their occurrence is uncommon. Relating their distribution to any specific suite of species or community structure is tenuous based on these limited data. There may be further opportunities to examine the faunal communities associated with pipehorses from additional surveys in the future. At the time of writing, the bycatch data from the 2002 Long-Term Monitoring scallop fishery-independent survey were being processed and therefore not available for inclusion for the present analyses.

16.3 METHODS

Associations between pipehorses and bycatch species were examined for two major trawl sectors – the scallop fishery and the shallow water eastern king prawn fishery.

16.3.1 The 2000 Long-Term Monitoring scallop fishery-independent survey

In 2000 the QFS annual Long-Term Monitoring Program sampled 374 sites throughout the scallop fishing grounds. Further details of the survey's objectives and design can be found in Dichmont et al. (2000). The survey observers also recorded the catch rate of pipehorses from every site and obtained a sub-sample of the bycatch from approximately every third site, resulting in 122 sub-samples (Figure 16.3.1). Four fishing vessels were chartered to undertake the survey over approximately 10 nights. The vessels were fitted with prawn trawl fishing nets (and not the larger mesh scallop nets) to capture and retain small/young size classes of scallops. Two vessels towed triple gear, one vessel towed quad gear and the fourth vessel towed a five-net configuration.

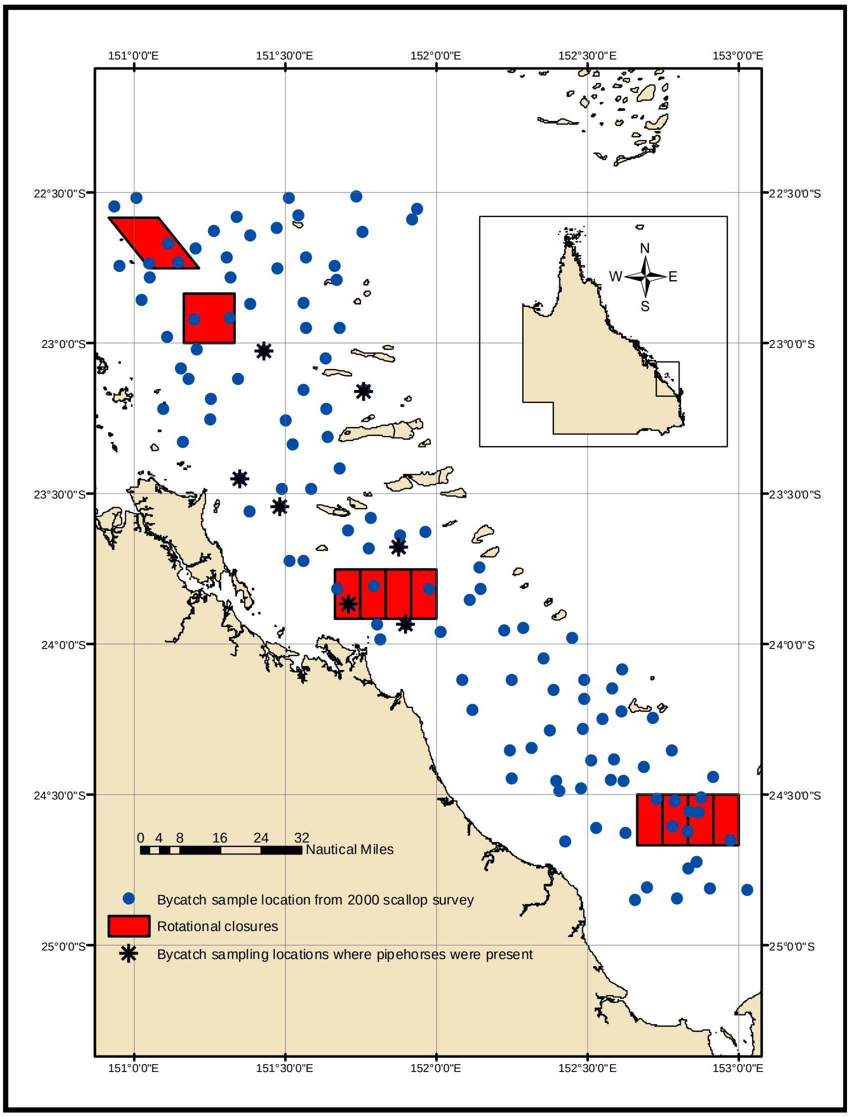


Figure 16.3.1. The location of 122 sites where bycatch was sampled during the 2000 Long Term Monitoring scallop fishery-independent survey. Pipehorses were present in trawls from seven of the 122 locations.

The catch rate of scallops from each vessel was standardised prior to the survey formally commencing. It is important to note that while the scallop catch rate was standardised to account for between-vessel variation, the catch rates of bycatch were not standardised between vessels. This is because the survey was primarily designed to account for variation in scallop abundance, rather than bycatch species. As such the catch rates of bycatch reported below are “raw” or unstandardised from the individual vessels.

16.3.2 Catch rates of bycatch

The general approach was to weigh the total bycatch from one net only immediately after retrieving the gear, and then retain, label and freeze a 10 kg (approximate) sub-sample. The accurate weight of the sub-sample was determined in the laboratory over the following months as the samples were sorted to species level, weighed and recorded. Because the bycatch was sub-sampled, the catch rates for individual species (number per swept area) were derived by extrapolating upwards using the following conversion:

$$Catch\ rate\ X_{si}\ m^{-2} = \left[Catch\ rate\ X\ in\ subsample_{\ si} \times \frac{Total\ bycatch\ weight_{\ i}}{Weight\ of\ subsample_{\ i}} \right] \div swept\ area\ of\ trawl_i\ m^{-2}$$

where X is the number of individuals of species s at trawl i.

Large or hazardous animals in the bycatch, or those with special conservation value, such as turtles, some elasmobranchs and sea snakes were removed from the bycatch and returned to the water. As such, they were not sub-sampled as the majority of species were, but rather their catch rates and weights were measured or estimated separately and recorded. Because they were not sub-sampled, their catch rates were not adjusted using the above conversion. The catch rate of pipehorses was recorded from every trawl (nets pooled) and converted to a catch rate per swept area. *Solegnathus* cf. *hardwickii* was the only species of pipehorse encountered during the 2000 Long-Term Monitoring scallop fishery-independent survey.

16.3.3 The shallow water eastern king prawn charter

Detailed sampling methods for this research charter are provided in Chapter 5. To briefly recapitulate, the charter was conducted over 10 nights in October 2001 to describe bycatch and test bycatch reduction devices (BRDs). Sixty sites were trawl sampled with two nets. A 10 kg sub-sample of the bycatch was retained and processed from each net resulting in 120 bycatch samples. The catch rate of pipehorses was recorded from every trawl and every net and converted to a catch rate per swept area.

16.3.4 Statistical analyses

The general statistical approach was to search for evidence of species groupings or clustering and then, where possible, examine how the pipehorse catch rates related to these patterns. Patterns in the bycatch species composition were investigated using cluster analysis and multidimensional scaling (MDS), methods that are commonly used to examine variation in the structure of aquatic faunal communities (Clarke and Green, 1988; Watson and Goeden, 1989; Gray et al., 1990; Watson et al.,, 1990; Clarke, 1993; Clarke and Ainsworth, 1993), and are particularly suited for datasets that contain a large number of species – characteristic of benthic trawl bycatch. The statistical software package PRIMER (Plymouth Routines in Multivariate Ecological Research) by Clarke and Warwick (1994) was used to apply the analyses.

The Bray-Curtis similarity index (Bray and Curtis, 1957) was used throughout to examine the similarity between each pair of samples and species groups and was based on catch rates of individual species in each trawl sample (number of individuals m^{-2}). Two data transformations were used (square-root and presence-absence), but only results from analyses that produced the lowest stress levels (i.e., highest dissimilarity between groups) are presented. MDS was carried out on species that were present in at least 5% of samples to avoid the species-sample matrix table being dominated by zeros.

16.3.5 Abiotic factors affecting bycatch composition

Only very few abiotic factors that may affect the faunal community structure were monitored throughout the 2000 Long-Term Monitoring scallop survey and shallow water eastern king prawn charter, as neither were specifically designed to assess the effects of abiotic factors on bycatch. The depth and latitude of each sampling site were recorded.

The main objective of the shallow water eastern king prawn charter was to test the effect of four different combinations of bycatch reduction devices (BRDs) and so the influence of BRD type on bycatch composition was also considered as an abiotic factor for this dataset. The types of BRDs examined are provided in Chapter 5.

Bottom temperature and salinity measures could have been obtained during both surveys but they are generally difficult to obtain on trawlers as lowering probes to the bottom requires the vessel to completely stop and rack the nets away from the propeller at each sampling location. In any case it is likely that there would have been minimal variation in both temperature and salinity between sampling sites. No other abiotic factors were considered, although future analyses might consider the carbonate fractions sediment data of Stevens (1995) referred to in Connolly et al. (2001).

16.4 RESULTS

16.4.1 Pipehorses and bycatch from the 2000 Long-Term Monitoring scallop fishery-independent survey

Of the 374 trawl sites sampled in the 2000 scallop survey, bycatch was sub-sampled from 122 sites (Figure 16.3.1). A total of 413 taxa were identified in the bycatch (Appendix 6). The numerically dominant species included the prawns (*Metapenaeopsis palmensis* and *Trachypenaeus curvirostris*), orange-spotted toadfish (*Torquigener pallimaculatus*), leather jackets (*Paramonacanthus otisensis* and *Paramonacanthus filicauda*), the green puller (*Pristotis jerdoni*), the portunid crab (*Portunus rubromarginatus*), orange-barred goatfish (*Upeneus asymmmetricus*), the longspine emperor (*Lethrinus genivittatus*), flatfish (*Engyprosopon grandisquama*) and pinkies (*Nemipterus theodorei*).

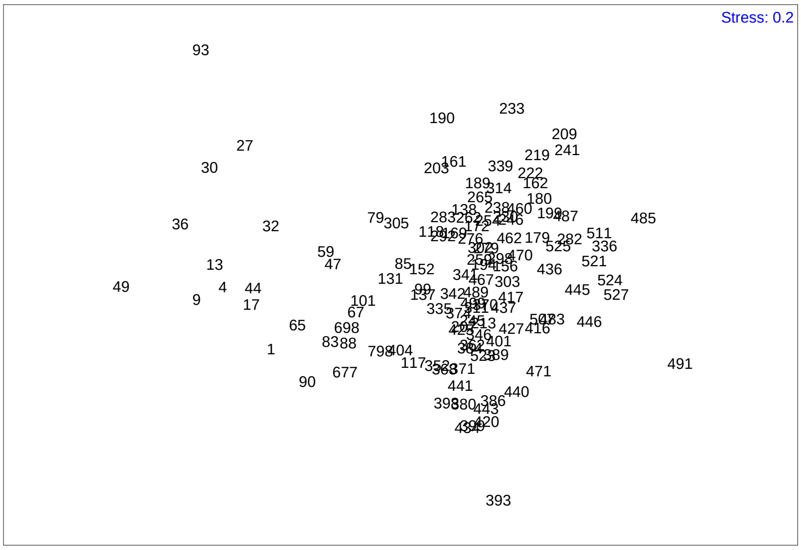
A total of 42 pipehorses were collected from all 374 sites and of these, 12 were caught at seven sites where bycatch was sub-sampled. Catch rates of *S.* cf. *hardwickii* were comparatively low and ranked 279 out of the 413 (Appendix 6).

Of the 413 taxa, 136 were present in 5% or more of the samples and therefore used in the MDS. No species occurred in every sample. The lizardfish *Saurida undosquamis* and the southern velvet prawn *Metapenaeopsis palmensis* both occurred in 89% of the samples. Other common species included *Torquigener pallimaculatus* (86% of samples), *Portunus rubromarginatus* (82% of samples), *Paramonacanthus otisensis*

(78% of samples) and *Nemipterus theodorei* (72% of samples). *S.* cf. *hardwickii* was present in 6% of samples.

MDS of the faunal groups using 1) individual samples and 2) samples categorised by latitude (to the nearest 0.1° S) are presented in Figure 16.4.1. In general, there was relatively little evidence of clustering of individual samples. However, when each sample was categorised by latitude there was evidence of faunal groupings along a north-south axis. Samples from the northern-most latitudes (latitudes 22.5, 22.6 and 22.7° S) clustered on the left side of Figure 16.4.1 while those from the southern-most latitudes (latitudes 24.6, 24.7 and 24.8° S) clustered on the right side.

MDS of 122 bycatch samples from the 2000 sacllop survey



MDS of 122 bycatch samples from the 2000 sacllop survey showing evidence of latitudinal grouping

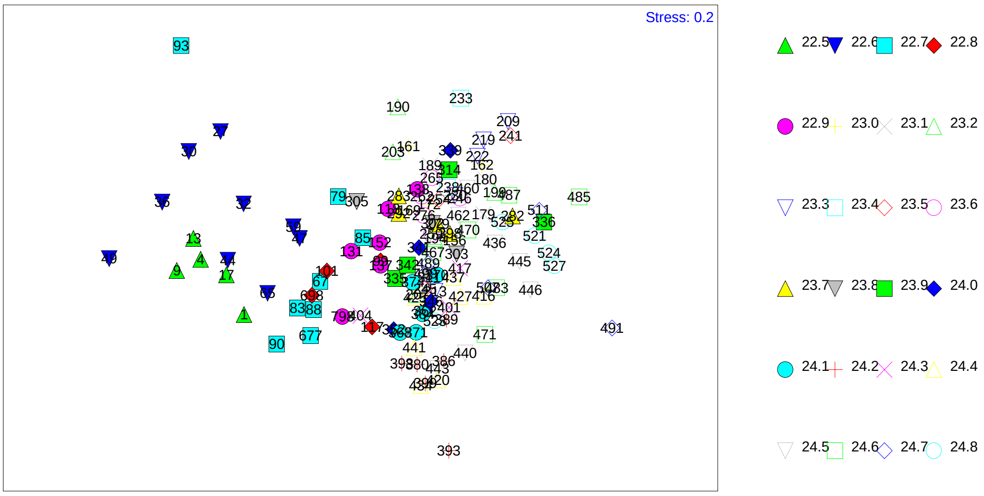
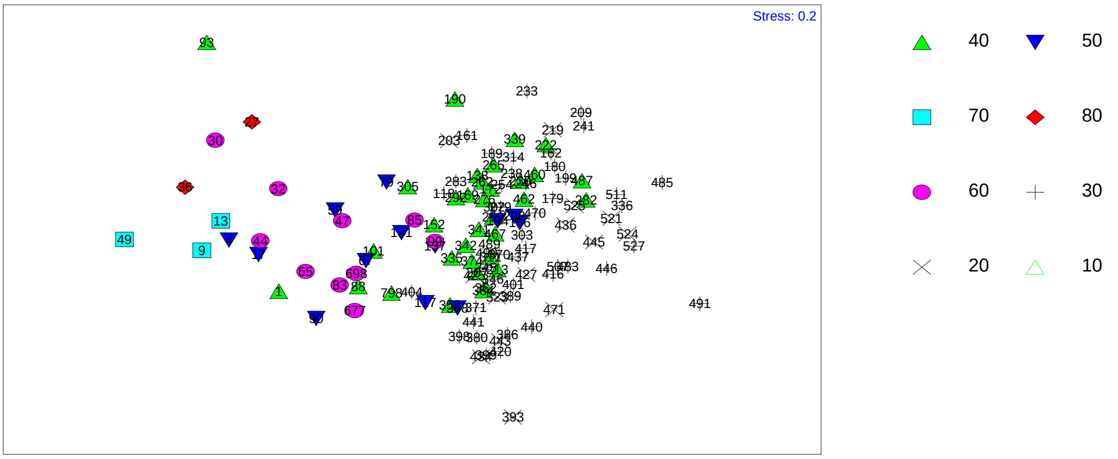


Figure 16.4.1. Multidimensional scaling of 122 samples of bycatch from the QFS 2000 scallop fishing ground survey, based on the presence/absence of 136 taxa. Each sample is labelled based on the site it was obtained from. Legend for lower graph is degrees latitude (to the nearest 0.1° S).

Figure 16.4.2 indicates that faunal community grouping also occurred with depth. The depths at sites where bycatch samples were obtained varied from 10 m to 80 m. A cluster of deepwater (70 m) sites (13, 49 and 9) can be seen on the left-hand side of Figure 16.4.2. Groups tend to be distributed across the graph, with deepwater groups on the left and shallow water groups on the right. The bycatch sample sites and depths where *S.* cf. *hardwickii* were caught are listed in Table 16.4.1 and show that pipehorses were caught in depths between 27 m and 48 m. Figure 16.4.2 indicates that the faunal communities with which *S.* cf. *hardwickii* was associated have the highest similarity to those communities associated with the 30 m and 40 m groupings.

MDS of 2000 scallop survey showing evidence of depth grouping



MDS of 2000 scallop survey bycatch in relation to S. cf. *hardwickii*

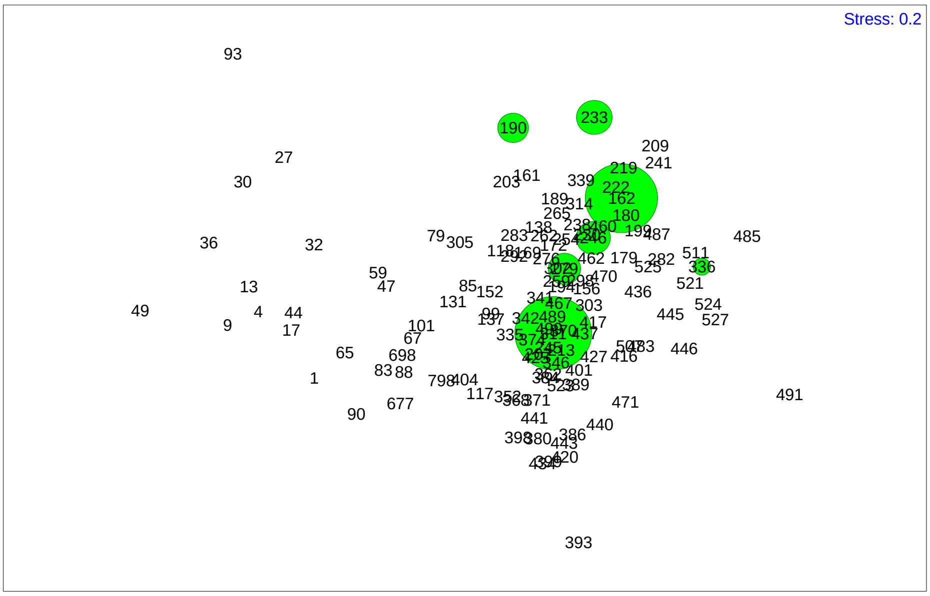


Figure 16.4.2. Multidimensional scaling of 122 samples of bycatch from the QFS 2000 Long-Term Monitoring scallop fishing ground survey, based on presence/absence of 136 taxa. Upper graph legend refers to the depth (m) category of each sample. The lower graph shows the distribution of *S.* cf. *hardwickii* relative to the other samples. Circle size is proportional to catch rate. Each sample is labelled with the site it was obtained from.

Table 16.4.1. Bycatch sampling sites and depths from the 2000 Long-Term Monitoring scallop survey grounds where pipehorses (*S.* cf. *hardwickii*) were obtained.

Sample site identification	Depth (m)
162	40
190	48
233	27
246	29
279	35
311	30
336	30

Species that account for 90% of the similarity in the 30 m and 40 m depth groups are listed in Table 16.4.2 and Table 16.4.3, respectively. Many of the species are common to both groups, including *Torquigener pallimaculatus, Paramonacanthus otisensis, Portunus rubromarginatus, Saurida undosquamis, Lethrinus genivittatus, Metapenaeopsis palmensis, Engyprosopon grandisquama, Inimicus sinensis, Pristotis jerdoni*. Because these species occur in both groups and explain much of similarity within groups, and because the MDS suggests that *S.* cf. *hardwickii* falls within these depth groups, it is reasonable to assume that *S.* cf. *hardwickii* may be associated with at least some of these species within the scallop fishing grounds.

Table 16.4.2. Species that contribute to the within-group similarity for the “30 m depth faunal grouping”, based on the 2000 scallop fishing grounds bycatch data. From “Simper” (similarity percentages) analysis (PRIMER software) using standardised presence/absence transformed catch rate data. * indicates positive correlation with *S.* cf. *hardwickii.*

Species	Average abundance	Average similarity	Sim/SD	Contribution%	Cumulative contribution %
Torquigener pallimaculatus	0.42	2.89	2.37	8.14	8.14
Paramonacanthus otisensis	0.34	2.51	2.07	7.06	15.2
Portunus rubromarginatus	0.32	2.37	1.94	6.65	21.85
Saurida undosquamis	0.36	2.36	1.69	6.63	28.48
Lethrinus genivittatus	0.32	1.94	1.34	5.47	33.95
Metapenaeopsis palmensis	0.33	1.79	1.22	5.04	38.99
Engyprosopon grandisquama	0.25	1.5	1.06	4.21	43.2
Inimicus sinensis	0.26	1.1	0.74	3.1	46.3
*Pristotis jerdoni**	0.24	0.97	0.74	2.73	49.04
Torquigener perlevis	0.2	0.89	0.59	2.51	51.55
Pentaceraster sp.	0.18	0.88	0.66	2.47	54.02
Apistus carinatus	0.23	0.87	0.63	2.43	56.46
Nemipterus theodorei	0.17	0.81	0.7	2.26	58.72
Siganus fuscescens	0.21	0.78	0.57	2.21	60.93
*Parapercis nebulosa**	0.19	0.78	0.64	2.19	63.11
Sorsogona tuberculata	0.21	0.74	0.56	2.08	65.19
Upeneus tragula	0.18	0.66	0.53	1.84	67.04
Trachinocephalus myops	0.15	0.64	0.55	1.8	68.83
Upeneus asymmetricus	0.15	0.59	0.49	1.65	70.48
Apogon nigripinnis	0.15	0.57	0.57	1.61	72.09
Trachypenaeus curvirostris	0.2	0.56	0.47	1.59	73.67
Euprymna sp.	0.16	0.56	0.52	1.57	75.24

Species	Average abundance	Average similarity	Sim/SD	Contribution%	Cumulative contribution %
Inegocia japonica	0.15	0.53	0.49	1.5	76.74
Metapenaeopsis lamellate	0.18	0.47	0.46	1.32	78.06
Callionymus limiceps	0.16	0.42	0.35	1.18	80.45
Arnoglossus intermedius	0.17	0.42	0.43	1.18	81.63
*Pentapodus paradiseus**	0.15	0.35	0.35	0.98	82.61
Chlamys sp.	0.16	0.34	0.38	0.96	83.56
Sepia papuensis	0.1	0.33	0.38	0.92	84.48
*Apogon poecilopterus**	0.14	0.26	0.33	0.73	85.22
Lepidotrigla argus	0.14	0.25	0.28	0.71	85.92
Chaetoderma penicilligera	0.11	0.24	0.29	0.68	86.6
Grammatobothus polyophthalmus	0.1	0.24	0.34	0.68	87.28
Sepia plangon	0.12	0.22	0.28	0.62	87.9
Erosa erosa	0.1	0.22	0.31	0.62	88.52
*Synchiropus rameus**	0.11	0.21	0.31	0.58	89.1
Choerodon cephalotes	0.1	0.2	0.24	0.56	89.66
Gymnocranius elongates	0.1	0.2	0.3	0.55	90.22

Table 16.4.3. Species that contribute to the within-group similarity for the “40 m depth faunal grouping”, based on the 2000 scallop fishing grounds bycatch data. From “Simper” (similarity percentages) analysis (PRIMER software) using standardised presence/absence transformed catch rate data. * indicates positive correlation with *S.* cf. *hardwickii.*

Species	Average abundance	Average similarity	Sim/SD	Contribution%	Cumulative contribution %
Metapenaeopsis palmensis	0.35	2.75	1.83	6.45	6.45
Portunus rubromarginatus	0.3	2.62	1.99	6.14	12.59
Saurida undosquamis	0.44	2.6	2	6.09	18.67
Torquigener pallimaculatus	0.33	2.59	2	6.07	24.74
Nemipterus theodorei	0.36	2.14	1.35	5.02	29.76
*Pristotis jerdoni**	0.33	2.04	1.17	4.78	34.54
Paramonacanthus otisensis	0.3	1.8	1.13	4.21	38.75
Trachinocephalus myops	0.34	1.69	1.02	3.97	42.73
Lethrinus genivittatus	0.33	1.6	1.04	3.76	46.49
Apistus carinatus	0.26	1.43	0.87	3.35	49.83
Engyprosopon grandisquama	0.34	1.43	0.95	3.35	53.18
Trachypenaeus curvirostris	0.24	1.21	0.75	2.84	56.02
Grammatobothus polyophthalmus	0.22	1.17	0.75	2.73	58.75
Inimicus sinensis	0.21	1.03	0.69	2.41	61.16
*Parapercis nebulosa**	0.21	0.99	0.69	2.32	63.47
Upeneus tragula	0.22	0.82	0.6	1.92	67.38
Pentapodus nagasakiensis	0.21	0.79	0.6	1.86	69.24
Lepidotrigla argus	0.22	0.74	0.55	1.74	70.98
Metapenaeopsis lamellate	0.18	0.67	0.55	1.57	72.56
Apogon nigripinnis	0.19	0.62	0.51	1.45	74.01
Chlamys sp. *1*	0.2	0.6	0.51	1.4	75.41
Euprymna sp.	0.17	0.6	0.51	1.4	76.81
Batrachomoeus dubius	0.18	0.58	0.51	1.35	78.16
Sepia plangon	0.19	0.52	0.47	1.23	79.39
Inegocia japonica	0.21	0.47	0.43	1.11	80.5
Sorsogona tuberculata	0.14	0.47	0.43	1.1	81.59

Species	Average abundance	Average similarity	Sim/SD	Contribution%	Cumulative contribution %
Pentaceraster sp.	0.11	0.46	0.39	1.07	82.66
*Apogon poecilopterus**	0.13	0.4	0.39	0.94	83.6
Upeneus asymmetricus	0.12	0.39	0.36	0.92	84.52
Pseudorhombus spinosis	0.13	0.37	0.36	0.88	85.4
Synodus sageneus	0.14	0.34	0.36	0.81	86.21
Dactylopus dactylopus	0.07	0.27	0.32	0.64	86.84
*Synchiropus rameus**	0.13	0.26	0.32	0.62	87.46
Callionymus japonicus	0.13	0.26	0.32	0.61	88.07
Arnoglossus intermedius	0.09	0.25	0.33	0.58	88.65
Stichopus sp.	0.08	0.24	0.29	0.56	89.22
Tetrosomus concatenates	0.09	0.22	0.29	0.53	89.74
Gymnocranius elongates	0.15	0.22	0.29	0.51	90.25

16.4.2 Pipehorses and bycatch faunal communities in the shallow water eastern king prawn fishing grounds

The project obtained bycatch measures and sub-samples from 1619 individual net trawls throughout the Queensland East Coast Trawl Fishery, including opportunistic measures from commercial vessels during their normal fishing activities and research charters. A list of all Syngnathids caught in the trawls sampled during the project is provided in Appendix 7.

A total of 95 Syngnathids, comprised of three *Filicampus tigris*, five *Hippocampus queenslandicus*, two *Solegnathus dunckeri* and 85 *S.* cf. *hardwickii*, were obtained from the 1619 trawls. The majority of *S.* cf. *hardwickii* (70 out of the 85) were obtained from the shallow water eastern king prawn charter (depths less than 50 fm) in south-east Queensland (see Chapter 5, Trip 59 in Appendix 7). The location of the 60 trawled sites, including those where *S.* cf. *hardwickii* were caught, is provided in Figure 16.4.3.

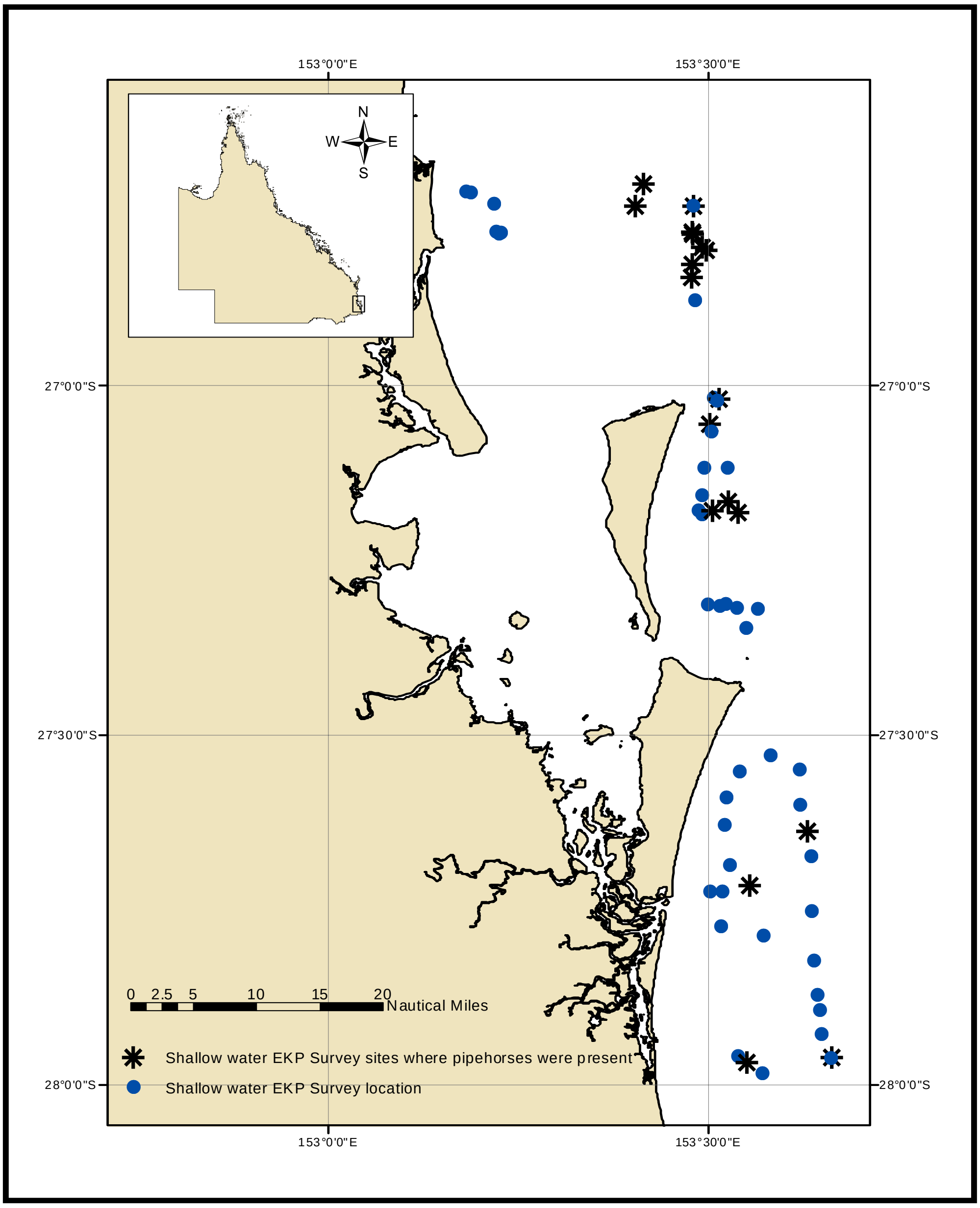


Figure 16.4.3. Location of the 60 sites trawl sampled in the shallow water eastern king prawn fishing grounds in October 2001. Each trawl was two nautical miles long. Locations where pipehorses were caught are also provided.

Another 10 individuals were caught in the king prawn fishing grounds from commercial vessel sampling and from the deepwater (> 50 fm) eastern king prawn charter in July 2002 (see Chapter 9). The remaining five *S.* cf. *hardwickii* were caught in commercial trawls in the scallop fishing grounds. The three *Filicampus tigris* were caught in the north Queensland tiger/endeavour prawn fishery. Four of the five *Hippocampus queenslandicus* and the two *S. dunckeri* were caught during the shallow water eastern king prawn charter.

S. cf. *hardwickii* were caught at 15 of the 60 locations (25% of sites, Figure 16.4.3) trawled during the shallow water eastern king prawn charter. At one site (site 16) a total of 15 individuals were caught. The average depth of sites where pipehorses were caught was about 76 m, which was much deeper than the sites where they were caught during the 1999 and 2000 scallop fishing grounds surveys (see Figure 3 in Connolly *et al.*, 2001).

The modal size of the 70 *S.* cf. *hardwickii* from the shallow water eastern king prawn charter was smaller than those reported by Connolly *et al.* (2001). Size class modes for *S.* cf. *hardwickii* obtained from processors from north (north of Bowen) and south Queensland (Mackay to Mooloolaba) were approximately 380 mm and 410 mm, respectively (Figure 10 in Connolly *et al.*, 2001). The modal size of *S.* cf. *hardwickii* from the shallow water eastern king prawn charter was 250 mm and the largest individual caught was 364 mm (Appendix 6).

A total of 250 taxa were identified in the bycatch from the shallow water eastern king prawn charter (page 15, Chapter 5). Species with the highest mean catch rates were the gurnard *Lepidotrigla argus*, portunid crab *Portunus argentatus*, Whitley's toadfish *Maxillicosta whitleyi,* stout whiting *Sillago robusta,* mottled wide-eyed flounder *Engyprosopon grandisquama,* flathead *Platycephalus longispinis* and dragonet *Callionymus calcaratus*, in decreasing order. Catch rates for *S.* cf. *hardwickii* and *S. dunckeri* were ranked 66 and 183, respectively.

MDS was carried out on 118 species present in 5% or more of the samples. No single species was present in all 120 samples. *L. argus* and *P. rubromarginatus* were present in 91% and 90% of samples, respectively. *S.* cf. *hardwickii* was present in 18% of samples. Stress values were 0.20 for the scallop fishing grounds survey MDS and 0.16 for the eastern king prawn bycatch, indicating higher between-group dissimilarity and greater group distinction in the eastern king prawn bycatch (Figure 16.4.4). The difference between groups was largely attributed to the depth of sample sites. This might be expected given the large range in depths sampled. For example, similarity percentage analysis (Simper analysis, PRIMER software) showed 90% dissimilarity between samples from 20 m and 90 m (Figure 16.4.4). Conversely dissimilarity between 80 m and 90 m samples was much lower (48%). Groups, based on depth, are distributed from left (shallow) to right (deep) (Figure 16.4.4). *S.* cf. *hardwickii* was most closely associated with the 80 m depth group. A list of the species that contribute to the within-group similarity of the 80 m depth grouping is provided in Table 16.4.4.

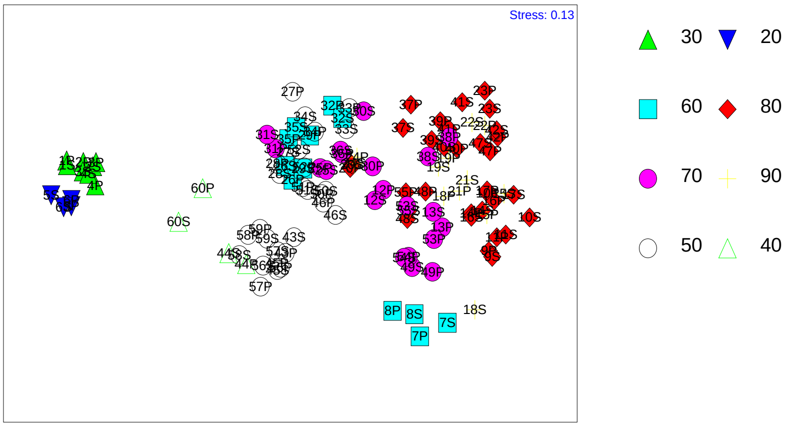
Table 16.4.4. Species that contribute to the within-group similarity for the "80 m depth faunal grouping" from the MDS of the shallow water eastern king prawn bycatch. Based on "Simper" (similarity percentages) analysis (PRIMER software) using standardised square-root transformed catch rate data. * indicates positive correlation with *S.* cf. *hardwickii.*

Species	**#Average abundance**	**Average similarity**	**Sim/SD**	**Contribution%**	**Cumulative contribution %**
Lepidotrigla argus	0.01	14.73	4.1	27.21	27.21
Portunus argentatus	0.01	9.78	1.92	18.07	45.28
*Nemipterus theodorei**	0	3.83	1.43	7.08	52.36
Optivus sp. *1**	0	3.34	1.21	6.16	58.53
Portunus rubromarginatus	0	2.5	1.57	4.61	63.14
Prionocidaris sp	0	1.9	1.25	3.51	66.65
Trachypenaeus curvirostris	0	1.71	1.43	3.16	69.8
Pseudorhombus tenuirastrum	0	1.67	1.37	3.08	72.88
Sepia plangon	0	1.58	1.35	2.92	75.8
*Upeneus tragula**	0	1.24	1.09	2.29	78.09
Callionymus japonicus	0	1.06	0.75	1.96	80.05
Engyprosopon macroptera	0	0.87	0.67	1.6	81.65
Tetrosomus concatenates	0	0.84	0.92	1.56	83.2
Trachinocephalus myops	0	0.84	0.8	1.55	84.76
Saurida grandisquamis	0	0.74	0.86	1.36	86.11
Maxillicosta whitleyi	0	0.71	0.39	1.32	87.43
*Ratabulus diversidens**	0	0.6	0.57	1.11	88.54
Platycephalus longispinis	0	0.46	0.29	0.86	89.4
Pseudorhombus dupliciocellatus	0	0.41	0.55	0.75	90.15

#Note: PRIMER's "average abundance" column outputs numbers to two decimal places only. Because the catch rates are generally so small (i.e., < 0.001 m^{-2}), they do not appear in the output.

Latitude had less influence than depth on the formation of bycatch groups and the different codend types were found to have no significant effect (see Chapter 5, Figure 5.4.3). This should not be interpreted as BRDs having no effect on bycatch catch rates, but rather that species composition is much more a function of location and depth. It should also be noted that not all four BRD types were towed at each site. Only two BRDs could be tested at each site because only two nets could be compared at each site (i.e., it was an incomplete block design).

MDS of shallow water eastern king prawn bycatch showing evidence of depth grouping



MDS of shallow water eastern king prawn bycatch in relation to S. cf hardwickii

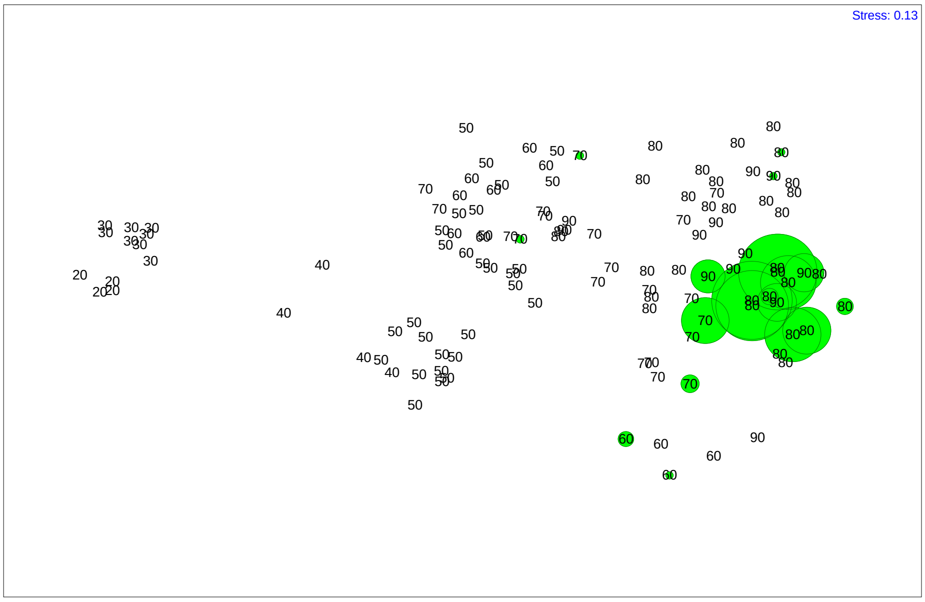


Figure 16.4.4. Multidimensional scaling of 120 samples (60 sites x 2 nets) of bycatch from the shallow water eastern king prawn charter in October 2001, based on the square-root transformation of catch rates. The upper graph shows clustering of bycatch groupings based on depth (to the nearest 10 m). The lower graph shows the distribution of *S.* cf. *hardwickii* in relation to the depth categories. Circle size reflects catch rate. Note the strong clustering of pipehorses at certain spatial locations and depths.

16.5 DISCUSSION

Two major differences between the 2000 Long-Term Monitoring scallop fishery-independent survey results and the shallow water eastern king prawn charter results were that 1) most *S.* cf. *hardwickii* were caught in comparatively shallow water (30–40 m) in the scallop fishing grounds compared to depths of about 80 m in the king prawn fishing grounds, and 2) the size range of pipehorses from the eastern king prawn fishing grounds was very small compared to those from the scallop fishery. In fact, the size range encountered in the eastern king prawn fishing grounds was considerably smaller than all of the compiled length-frequency data from north and south Queensland regions (see Figure 10 in Connolly et al., 2001).

Although speculative, the small size classes may indicate that trawling occurred in juvenile/sub-adult habitats. Alternatively, the absence of large size classes could also reflect heavy fishing pressure. The difference between depths and size classes might also suggest that *S.* cf. *hardwickii* moves from deepwater (> 70 m) to shallow (30–40 m) as it grows. The northern hemisphere pipefish *Syngnathus fuscus* has been reported to migrate up to hundreds of kilometres from shallow to deep water during winter (Lazarri and Able, 1990).

16.5.1 Conclusions from MDS

The MDS of the 2000 Long-Term Monitoring scallop fishery-independent survey bycatch data indicated that *S.* cf. *hardwickii* was associated with specific communities related to depth, specifically depths of 30–40 m and identified those species that explain much of the similarity within the 30 m and 40 m faunal groupings. The MDS of the shallow water eastern king bycatch data indicated greater group dissimilarity (stress = 0.16) than the scallop data (stress = 0.20) and therefore greater ability to distinguish groups, probably because it sampled over a wider range of depths. *S.* cf. *hardwickii* was associated with the 80 m group in the king prawn samples.

The analyses have therefore identified three faunal depth groupings [two from the scallop fishing grounds data (30 m and 40 m groups) and one from the eastern king prawn data (80 m group)] that *S.* cf. *hardwickii* may be associated with. The species that contribute most to the similarity within these groups are not necessarily those species that associate with *S.* cf. *hardwickii*, but rather they are species whose catch rates show greatest similarity within each depth category. For example, *Lepidotrigla argus* (a species listed in all three similarity tables) does not necessarily co-occur with *S.* cf. *hardwickii*. *L. argus* is common to many sites in both the scallop and eastern king prawn datasets, but it is important for accounting for within-group similarity because its catch rates are very similar within particular depth categories.

Some of the species that explain the within-group similarity may be positively or negatively correlated with *S.* cf. *hardwickii.* Those species whose catch rates were positively correlated with *S.* cf. *hardwickii* are most likely to co-occur or associate with pipehorses. For example, in the scallop bycatch analysis species that accounted for similarity in the 30 m and 40 m groups and were positively correlated with *S.* cf. *hardwickii* were the green puller *Pristosis jerdoni,* the cardinal fish *Apogon poecilopterus,* the bar-faced weaver *Parapercis nebulosa,* the whiptail *Pentapodus paradiseus* and high-finned dragonet *Synchiropus rameus.*

Other species in the scallop bycatch that did not contribute significantly to the 30 m and 40 m within-group similarity but did have high positive correlation with *S.* cf. *hardwickii* were *Apogon brevicaudatus* and an unidentified ascidian. Their correlation coefficients were 0.52 and 0.42, respectively.

In the bycatch from the shallow water eastern king prawn fishing grounds, those species that contributed to the 80 m group similarity and had a positive correlation with *S.* cf. *hardwickii* were the orange-freckled flathead *Ratabulus diversidens* and the violet roughy *Optivus* sp. *1*, threadfin bream *Nemipterus theodorei* and goatfish *Upeneus tragula*. Interestingly, there were more significant correlations with *S.* cf. *hardwickii* in the king prawn bycatch data than in the scallop bycatch data. Species that had marked negative correlations with *S.* cf. *hardwickii*, but still contributed to the 80 m within-group similarity were the grinner *Saurida grandisquamis* and the flathead *Platycephalus longispinis* – both with correlation coefficients of –0.25. Other species in the king prawn bycatch that were not found to contribute significantly to the 80 m group similarity but did have significant positive correlations with *S.* cf. *hardwickii* were the goosefish *Lophiomus setigerus* (correlation coefficient of 0.58) and grinner *Saurida filamentosa* (correlation coefficient of 0.48).

It should be noted that these findings are preliminary and exploratory and should be interpreted with caution. More detailed abiotic information is required on the sample sites where the bycatch and pipehorses were collected. Collectively the results suggest that within the scallop fishing grounds and the shallow water eastern king prawn fishing grounds, *S.* cf. *hardwickii* occurs in specific depth ranges. Bycatch communities in both sectors can be grouped according to depth. Those species that are likely to co-exist with pipehorses differ between the two sectors.

16.6 REFERENCES

Bray, J.R., Curtis, J.T., 1957. An ordination of the upland forest communities of Southern Wisconsin. Ecol. Monogr. 27, 325-349.

Clarke, K.R., 1993. Non-parametric multivariate analyses of changes in community structure. Aust. J. Ecol. 18, 117-143.

Clarke, K.R., Green, R.H., 1988. Statistical design and analysis for a ‘biological effects’ study. Mar. Ecol. Prog. Ser. 46, 213-226.

Clarke, K.R., Ainsworth, M., 1993. A method of linking multivariate community structure to environmental variables. Mar. Ecol. Prog. Ser. 92, 205-219.

Clarke, K.R., Warrick, R.M., 1994. Change in marine communities: an approach to statistical analysis and interpretation. Plymouth: Plymouth Marine Laboratories, 144 pp.

Connolly, R. M., Cronin, E. R., Thomas, B. E., 2001. Trawl bycatch of syngnathids in Queensland: catch rates, distribution and population biology of Solegnathus pipehorses (seadragons). FRDC Report 1999/124. 57 pages.

Courtney, A. J., 2002. Research results on the effects of bycatch reduction devices in the eastern king prawn fishery. Queensland Fisherman 20(6):20-23.

Dichmont, C. M., Dredge, M. C. L., Yeomans, K., 2000. The first large-scale fishery-independent survey of the saucer scallop *Amusium japonicum balloti* in Queensland, Australia. J. Shellfish. Res. 19(2): 731-739.

Field, J.G., Clarke, K.R. Warwick, R.M., 1982. A practical strategy for analysing multispecies distribution patterns. Mar. Ecol. Prog. Ser. 8, 37-52.

Gray, C.A., McDonall, V.C., Reid, D.D., 1990. By-catch from prawn trawling in the Hawkesbury River, New South Wales: species composition, distribution and abundance. Aust. J. Mar. Freshwater Res. 41(1), 13-26.

Harris, A., Ward, P., 1999. Non-target species in Australia's commonwealth fisheries. A critical review. Bureau of Rural Sciences, Canberra. Australia. 152 pp.

Lane, P.W., Payne, R.W., Ainsley, A.E., Bicknell, K.E., Digby, P.G.N., Harding, S.A., Leech, P. K., Simpson, H. R., Todd, A. D., Verrier, P. J., While, R. P., Gowe, J. C., Tunnicliffe Wilson, G., Paterson, L. J., 1988. GenStat 5 Committee of the Statistics Department Rothamsted Experimental Station. GenStat 5 Reference Manual. Oxford Science Publications. 749 pp.

Lazzari, M. A., Able, K. W., 1990. Northern pipefish, *Syngnathus fuscus,* occurrences over the Mid-Atlantic Bight continental shelf: evidence of seasonal migration. Environ. Biol. Fish. 27:177-85.

McShane, P.E., Hall, S.J., Carrick, N.A., 1999. Trophic consequences of prawn trawling: linking bycatch to benthos. In: Buxton, C., Eayrs, S., (Eds) Establishing meaningful targets for bycatch reduction in Australian fisheries pp. 106-112. Australian Society for Fish Biology Workshop Proceedings, Hobart 24-25 September 1998.

Stevens, T. F., 1995. Queensland marine habitats – a biophysical classification at the meso-scale for conservation planning. In: Muldoon, J. (ed.) Towards a Marine Rationalisation for Australia. Ocean Rescue 2000 Workshop Series Publication No. 1, pp 95-112. Great Barrier Reef Marine Park Authority, Canberra.

Watson, R.A., Goeden, G., 1989. Temporal and spatial zonation of the demersal trawl fauna of the central Great Barrier Reef. Mem. Qld. Mus., pp. 611-620.

Watson, R.A., Dredge, M.C.L., Maher, D.G., 1990. Spatial and seasonal variation in demersal trawl fauna associated with a prawn fishery on the central Great Barrier Reef, Australia. Aust. J. Mar. Freshwater Res. 41, 65-77.

17 Aspects of the reproductive biology and growth of Balmain bugs *Ibacus* spp. (Scyllaridae)

J. A. Haddy, A. J. Courtney and D. P. Roy

17.1 ABSTRACT

This chapter describes the reproductive biology and growth of *Ibacus alticrenatus*, *I. brucei* and *I. chacei* from the east coast of Queensland, Australia. Reproductive cycles, sizes at maturity, sex ratios, morphological data, egg sizes, brood fecundities, length-frequency distributions and growth parameters are described. *I. chacei* numerically dominated both the commercial and research charter samples and were followed by *I. brucei* and *I. alticrenatus* in abundance, respectively. Seasonal reproductive data indicated that *I. brucei* and *I. chacei* had an annual cycle of reproduction, with oviposition and hatching occurring earlier and over a shorter period in *I. brucei*. Gonadal maturation in ovigerous *I. chacei* suggested that more than one brood could be produced in a spawning season; however, reproductive activity was geographically restricted. Carapace lengths of ovigerous lobsters ranged from 38.2 to 52.0 mm for *I. alticrenatus*, 44.6 to 69.7 mm for *I. brucei* and 53.7 to 76.2 mm for *I. chacei*. Brood fecundity was size dependent and highest in *I. brucei* (2049 to 61,339) but markedly lower in *I. chacei* (2117 to 28,793) and *I. alticrenatus* (1734 to 14,762). Egg size in all three species were independent of carapace length, positively related to developmental stage, and ranged from 0.94 to 1.29 mm for *I. alticrenatus*, 0.73 to 1.01 mm for *I. brucei* and 1.02 to 1.37 mm for *I. chacei*. Monthly length-frequency distributions for *I. chacei* displayed marked multi-modality and indicated a prolonged recruitment period with moulting occurring 3 to 4 times within their first year post-recruitment. Growth curves of *I. chacei* indicated that females reached sexual maturity between 1.7 and 2 years post-settlement and that individuals approached their L_{max} in 5 to 7 years. These results are discussed in relation to comparisons between each species and other members of the Scyllaridae family, and provide invaluable biological information for the development of sustainable management strategies for Queensland's *Ibacus* species.

17.2 INTRODUCTION

Balmain bugs are marine lobsters of the genus *Ibacus* and family Scyllaridae. Currently there are eight known species, with *I. alticrenatus* (Bate, 1888), *I. brevipes* (Bate, 1888), *I. brucei* (Holthuis, 1977), *I. chacei* (Brown, 1998) and *I. peronii* (Leach, 1815) known to occur in Queensland waters (Brown and Holthuis, 1998). Balmain bugs typically inhabit soft bottom substrates such as sand, mud and clay that allows the lobsters to bury (Holthuis, 1991). Consequently they are commonly taken during demersal trawling as incidental byproduct; however, increased consumer awareness, expanding markets and price increases have resulted in fishers specifically targeting these species (Kaiola et al., 1993; Stewart et al., 1997). The reported annual landings of Balmain bugs from Queensland's waters during 2000, 2001 and 2002 were 72, 61 and 55 tonnes respectively, worth approximately A$650,000 – 850,000. However, despite their economic importance they have received little research attention. As a consequence very little is known about the population dynamics of Queensland's *Ibacus* stocks and it is currently unknown whether present exploitation levels are sustainable.

Although the reproductive biology and growth of clawed and spiny lobsters is well documented (see reviews in Aiken, 1980; Aiken and Waddy, 1980; Breen, 1994; Chubb, 1994; Quackenbush, 1994) information on scyllarid lobsters is limited to a few commercially important species. These include *Scyllarides latus* (Martins, 1985; Spanier and Lavalli, 1998) *Scyllarides nodifer* (Stimpson, 1866) (Lyons, 1970; Hardwick and Cline, 1990), *Scyllarides squammosus* (H. Milne Edwards, 1837) (DeMartini and Williams, 2001), *Thenus orientalis* (Lund, 1793) (Hossain, 1975; Jones, 1988; Courtney et al., 2001; Zhu et al., 2001), *Thenus indicus* (Lund, 1793) (Jones, 1988; Courtney et al., 2001), *I. peronii* and *I. chacei* (Stewart and Kennelly, 1997; Stewart et al., 1997; Stewart and Kennelly, 1998; Stewart and Kennelly, 2000). Size at sexual maturity, fecundity, seasonal reproductive profiles, spawning sites and growth rates are some of the most important life history parameters needed for stock assessment and management of sustainable exploitation levels (Chubb, 1994). Furthermore as Balmain bugs are mainly an incidental byproduct of demersal trawling, limiting fishing effort and changing mesh sizes are not appropriate management strategies. However, as discard mortality of trawl-caught crustaceans is relatively low compared to fish (Hill and Wassenberg, 1990), minimum legal size limits (MLS) are one of the few appropriate management measures available because undersized Balmain bugs can be returned to the water alive. Although a MLS of 100 mm carapace width (CW) on Queensland's Balmain bugs has recently been introduced, there is considerable concern that the "one size limit fits all" approach is inappropriate. Moreover, this size limit has been introduced without quantitative data from Queensland's *Ibacus* spp. The aim of this study was to describe the reproductive biology and growth of Queensland's *Ibacus* spp., to assist in the development of sustainable management strategies. Results from this study were used to recommend changes to the MLS of *Ibacus* spp. in Queensland.

17.3 MATERIALS AND METHODS

17.3.1 Sample processing

Ibacus alticrenatus, I. brucei and *I. chacei* were obtained from two trawl research charters (Queensland Department of Primary Industries (QDPI) shallow water (50–100 m) charter 10–19 October 2001, and QDPI deepwater (100–200 m) charter 17-29 July 2002; Courtney, 2002 and Courtney and Campbell, 2003) and opportunistically from commercial trawl fishers operating from the ports of Gladstone, Bundaberg and Mooloolaba (Figure 17.3.1). Obtaining regular monthly samples was reliant upon commercial trawl fishers donating samples. Samples were frozen and stored until processed in the laboratory, with fishers providing details of capture date, location and depth. Once thawed, total weight (TW), carapace length (CL), carapace width (CW), sex, gonad weight (females only), macroscopic gonad condition, presence of ovigerous setae and stage of egg development was recorded for each specimen. Carapace length was measured between the anterior mid-point of the antennular somite to the posterior margin of the carapace, and carapace width from the widest point between the first and second post-cervical spines using graduated vernier callipers to 0.1 mm. Sex was assigned from the external locations of the genital openings. Criteria for macroscopic staging of gonads were obtained from Stewart et al., (1997) and are detailed in Table 17.3.1. Gonadosomatic indices (GSI) were calculated as gonad weight/total weight x 100. Extruded eggs were classified as: (1) Early, orange with no pigmentation; (2) Mid, orange with eye-spots visible; or (3) Late, brown with eye-spots visible.

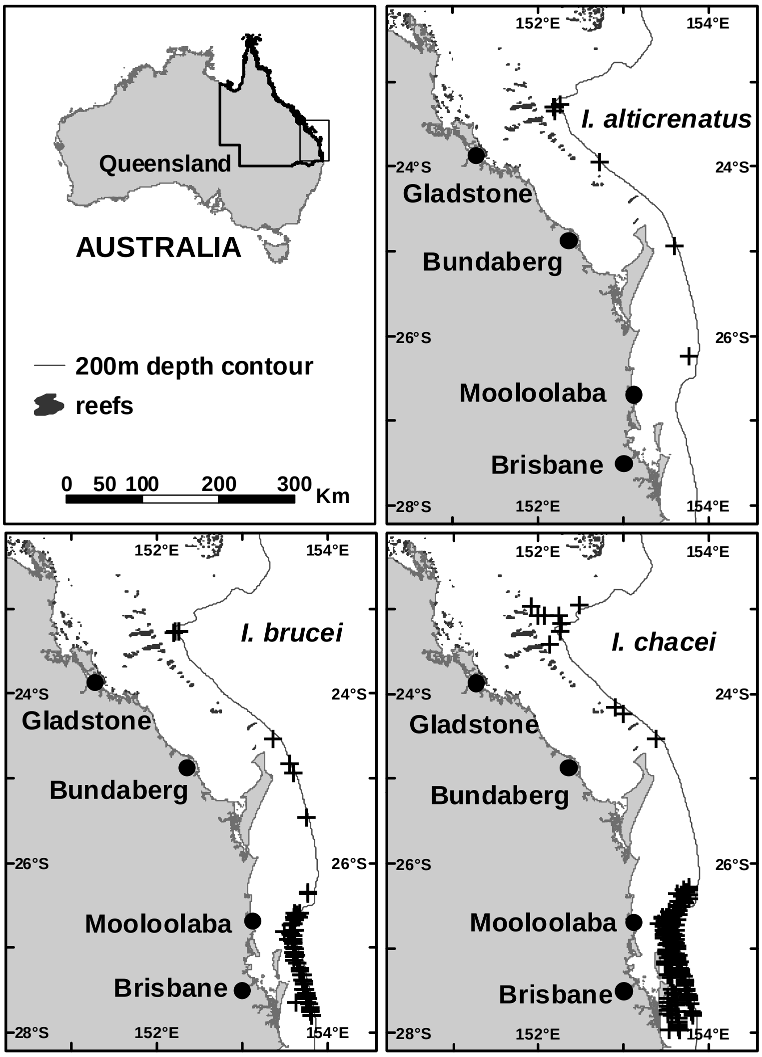


Figure 17.3.1. Sample location sites. Crosses indicate exact locations where samples were obtained.

Table 17.3.1. Macroscopic descriptions of ovarian development in *Ibacus* spp.

Stage	Macroscopic description
1. Immature	Ovaries clear to white, small, straight and narrow. Individual oocytes not visible.
2. Immature / regressed	Ovaries cream to yellow and small. Individual oocytes not visible.
3. Maturing	Ovaries orange enlarged throughout their length but not convoluted. Individual oocytes are just visible through the ovary wall.
4. Mature	Ovaries bright orange, swollen and convoluted, filling all available space in the cephalothoracic region. Individual oocytes are clearly visible through the ovary wall.
5. Spent	Ovaries cream to yellow/orange, large but not convoluted with flaccid and granular appearance. A few residual oocytes can sometimes be seen through the ovary wall.

17.3.2 Fecundity and egg size

Estimates of brood fecundity (BF) were determined using a gravimetric method. Ovigerous females were placed onto blotting paper and allowed to drain. The entire egg mass was carefully stripped from the pleopods using curved forceps and weighed (± l mg). A sub-sample of approximately 0.1 g of the egg mass was weighed (± 0.01 mg) and fixed in 70% ethanol. Egg clumps in the sub-sample were separated into individual eggs by dissolving the egg stalks with sodium hypochlorite. Once separated the sub-sample was drained, rinsed and resuspended in 70% ethanol, poured into a glass petrie dish and scanned. The total number of eggs in the sub-sample was determined using computer image analysis (Image-Pro Plus version 4.5). Brood fecundity was estimated by simple proportion. The mean diameters of freshly thawed eggs were determined using a dissecting microscope fitted with a digital camera and measured using image analysis software. Ninety diameter measurements were automatically measured for each egg to produce mean individual egg diameters. Between 10 and 58 eggs were measured for each female processed.

17.3.3 Population parameter estimates

Estimates of the von Bertalanffy growth parameters for male and female *I. chacei* were generated using a least squares method based on pooled modal size (CL mm) class frequencies and considered two possible moulting scenarios, where individuals either moulted three or four times during the 12-month period after first recruiting to the fishery. As the gender of juveniles could not be discerned, their length-frequency data were pooled and distributed equally to males and females. Moult increments were defined as the difference in CL between peak values of successive modal size classes in the pooled length-frequency distributions for *I. chacei*. Carapace sizes at T_0 and $T_{12\ \mathrm{months}}$ were determined from the modal peaks of the pooled length frequency distributions for each sex. The asymptotic length (L_∞) used to calculate the Brody growth coefficient k was set at the maximum observed CL for males and females, respectively.

Seasonal GSI data for *I. chacei* were arcsine square-root transformed and analysed by a general linear model and Tukey’s multiple comparison of means using the SAS statistical package. Sub-adult size classes (based on the smallest mature animal observed) were omitted from seasonal reproductive data to ensure that immature values did not bias mean GSI values. Regression analysis between fecundity, carapace size, egg size and egg stages were conducted using the least squares procedures of Microsoft Excel and GenStat 6 (GenStat 6, 2002).

17.4 RESULTS

Sample details and morphometric measurements for all three *Ibacus* species are provided in Table 17.4.1 and Table 17.4.2, respectively. Regular monthly samples from deep-water (> 100 m) could not be obtained year round due to fishing effort targeting other more valuable species [i.e., eastern king prawns *Penaeus plebejus* (Hess, 1865) inhabiting shallow water (< 100 m) in the summer months]. Of a total of 13,221 Balmain bugs, *I. chacei* dominated both the commercial and research charter samples. Total numbers of lobsters from all samples were 10,396, 2065 and 760 for *I. chacei*, *I. brucei* and *I. alticrenatus*, respectively. The overall sex ratios (female:male) from all samples combined were 1:1.28 for *I. alticrenatus,* 1:1.05 for *I. brucei* and

1:1.07 for *I. chacei*. Pooled length-frequency distributions for *I. alticrenatus* were unimodal, whereas *I. brucei* and *I. chacei* displayed multi-modal distributions (Figure **17.4.1**).

Table 17.4.1. Details of sample collection dates, depth collected and total numbers of *Ibacus alticrenatus*, *Ibacus brucei* and *Ibacus chacei*

Species	**Number of samples**	**Collection date range**	**Depth range (m)**	**Total numbers**		
				Juveniles	**Females**	**Males**
I. alticrenatus	9	27.4.2002 – 9.12.2002	118–258	-	337	423
I. brucei	17	4.4.2002 – 26.11.2002	117–230	41	988	1036
I. chacei	48	10.10.2001 – 24.3.2003	58–238	2497	3816	4083

Table 17.4.2. Regression parameters for the carapace length (CL) – total weight (TW) relationship and carapace width (CW) – carapace length relationship for *Ibacus alticrenatus*, *Ibacus brucei* and *Ibacus chacei*

	$TW = a*CL^{b}$				**$CW = a*CL^{-b}$**				**CL_{MAX}**
	N	**a**	**b**	**r^2**	**N**	**a**	**b**	**r^2**	**mm**
I. alticrenatus Male	205	0.0007	2.9031	0.96	170	1.5884	0.4355	0.93	54.7
I. alticrenatus Female	284	0.0016	2.6980	0.93	214	1.4779	4.8071	0.93	56.5
I. brucei Male	626	0.0004	3.0419	0.99	489	1.4718	8.5795	0.97	65.7
I. brucei Female	583	0.0003	3.1211	0.99	374	1.5083	7.0743	0.98	74.4
I. chacei Male	1868	0.0004	3.1069	0.99	691	1.9032	3.0540	0.99	72.9
I. chacei Female	1739	0.0004	3.0807	0.99	691	1.8834	2.6899	0.99	81.0

During the research charters off Mooloolaba, *I. chacei* accounted for 99.8% (n = 1259) and 69.3% (n = 1101) of the Balmain bugs landed in the shallow (< 100 m) and deep (> 100 m) water charters respectively. In contrast, *I. brucei* was moderately common in the deep water contributing 30.6% (n = 486) to the Balmain bug catch, whereas *I. alticrenatus* was rare with only one individual being caught in the deep water (0.1%). Catch rates of *I. chacei* and *I. brucei* in shallow water averaged 5.85 ± 1.08 (S.E.) individuals per hectare (ha^{-1}) (range 0–39.65 individuals ha^{-1}) and 0.01 ± 0.01 individuals ha^{-1} (range 0–0.28 individuals ha^{-1}), respectively. However, in the deep water, catch rates of *I. chacei* fell to 1.78 ± 0.34 (range 0–11.65 individuals ha^{-1}) whereas catch rates of *I. brucei* rose to 0.87 ± 0.20 individuals ha^{-1} (range 0–7.54 individuals ha^{-1}).

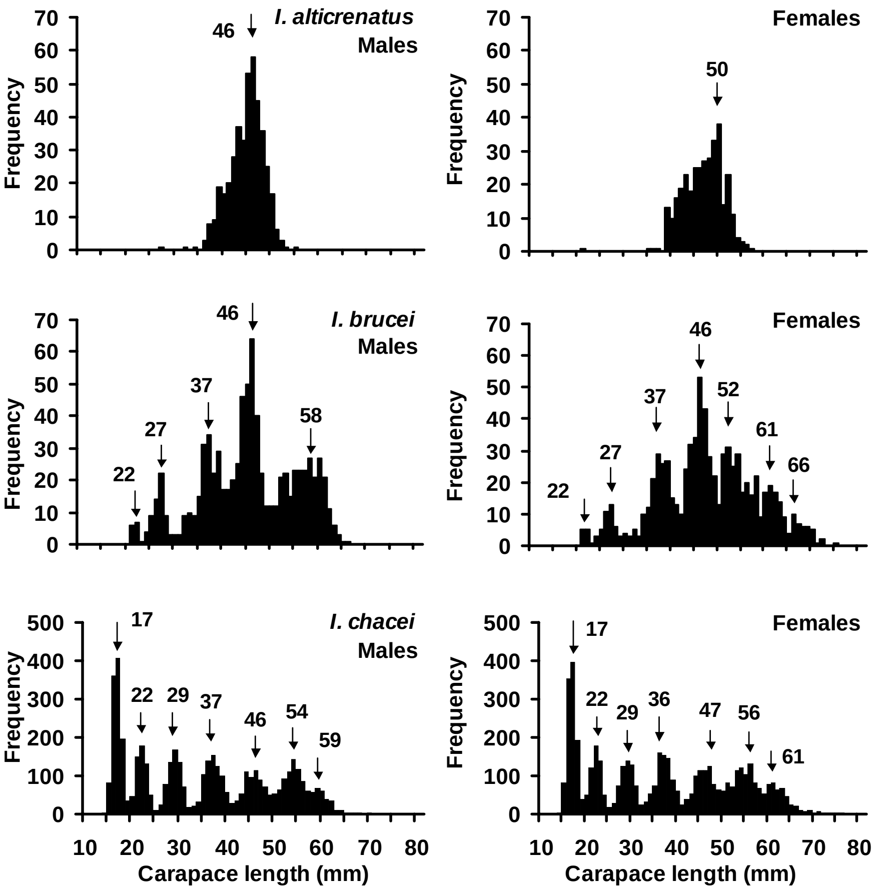


Figure 17.4.1. Carapace length-frequency distributions for male and female *Ibacus alticrenatus, Ibacus bruce*i and *Ibacus chacei* (all dates and locations pooled). Arrows indicate peak values of each size class mode.

17.4.1 Species accounts

Ibacus chacei

The GSI of female *I. chacei* caught off Mooloolaba was relatively low throughout the study period with a single peak in January 2003 (Figure 17.4.2). This sample comprised the largest individuals collected during the study and was obtained from the northernmost region of Mooloolaba. Proportions of reproductively active females (ovarian stages 3–5) were low throughout, with the majority of individuals possessing stage 1 or stage 2 ovaries (Figure 17.4.3).

Three ovigerous females were collected off Mooloolaba in October 2001 and January 2003. In contrast, the mean GSI of female *I. chacei* off Gladstone–Bundaberg was low in December 2001, rose to peak levels in April 2002 and gradually declined to their lowest values in December 2002. Thereafter the mean GSI again rose markedly. Proportions of reproductively inactive females (stages 1–2) were generally low off Gladstone–Bundaberg; however, proportions of stage 2 females were high in December 2002 (Figure 17.4.3). Proportions of reproductively active females displayed a clear seasonal cycle of ovarian maturation, with developing (stage 3) females abundant over summer and autumn, fully mature females (stage 4) abundant over autumn and winter, and spent females (stage 5) abundant from late winter to early spring.

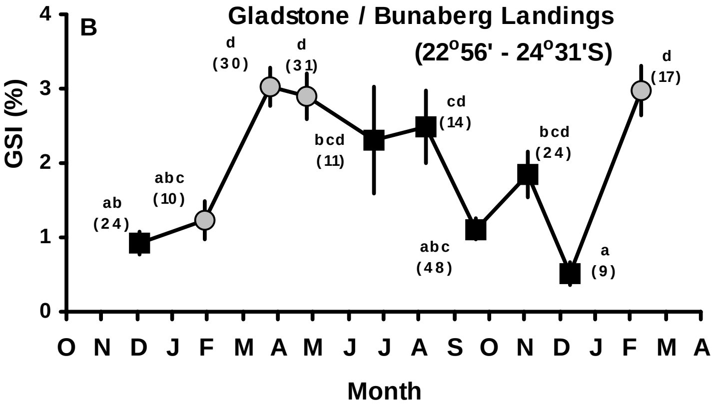


Figure 17.4.2. Seasonal changes in mean gonadosomatic index (GSI ± S.E.) from adult female *Ibacus chacei* (> 54 mm CL) caught off (A) Mooloolaba or (B) Gladstone–Bundaberg from October 2001 to March 2003. ■ Indicates samples where ovigerous females were present. Values that are significantly different have different superscripts ($P < 0.05$). Sample numbers given in parentheses.

Ovigerous females were most abundant in September but were present from late June to January. Proportions of ovigerous females possessing early, mid- and late stage eggs were highest in June–Aug, September–October and November–January, respectively. In some cases ovigerous females also possessed developing or fully mature ovaries. All of these individuals possessed mid- or late stage eggs, with the majority being caught early in the season (August). Ovigerous females ranged in size from 53.7 to 76.2 mm CL (Figure 17.4.4). Brood fecundity (BF) ranged from 2117 – 28,793 eggs, was size dependent and best described by the linear regression, BF = 0.8849*CL –43.405 ($r^2 = 0.48$). Egg size ranged from 1.02 – 1.37 mm, was independent of lobster size and increased ($P < 0.001$; $r^2 = 0.33$) with egg stage (Figure 17.4.5). The mean number of eggs per gram body weight for ovigerous females was 80 ± 3 eggs g^{-1} (S.E.; range 21–154). Two ovigerous females with early stage eggs were observed carrying residual spermatophoric masses. Spermatophoric masses were gelatinous, an opaque white colour and deposited in two strips along the lateral undersides of the anterior abdomen.

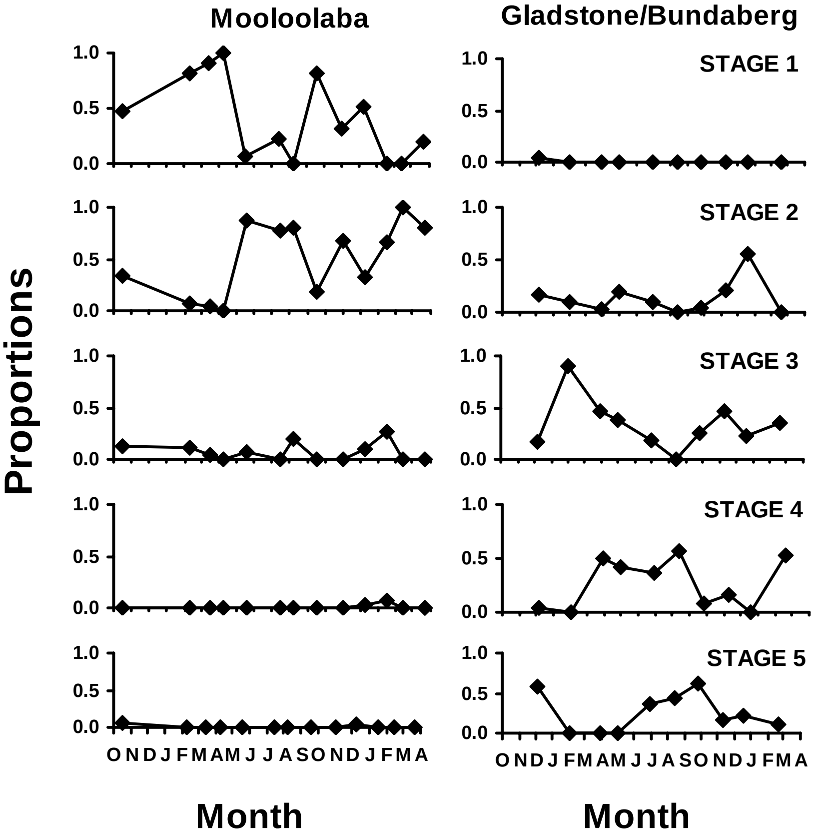


Figure 17.4.3. Seasonal changes in the proportions of adult female *Ibacus chacei* caught off Mooloolaba or Gladstone–Bundaberg in relation to ovarian maturation stages

Recently recruited individuals (14–20 mm CL) were present on the fishing grounds over a prolonged period, but were most abundant in February (Figure 17.4.6 and Figure 17.4.7). Although length-frequency distributions did not display clear modal progression, there was a general tendency for additional modes to appear over time, and indicated that juveniles recruiting in February moulted three to four times in their first year after recruiting to the fishery.

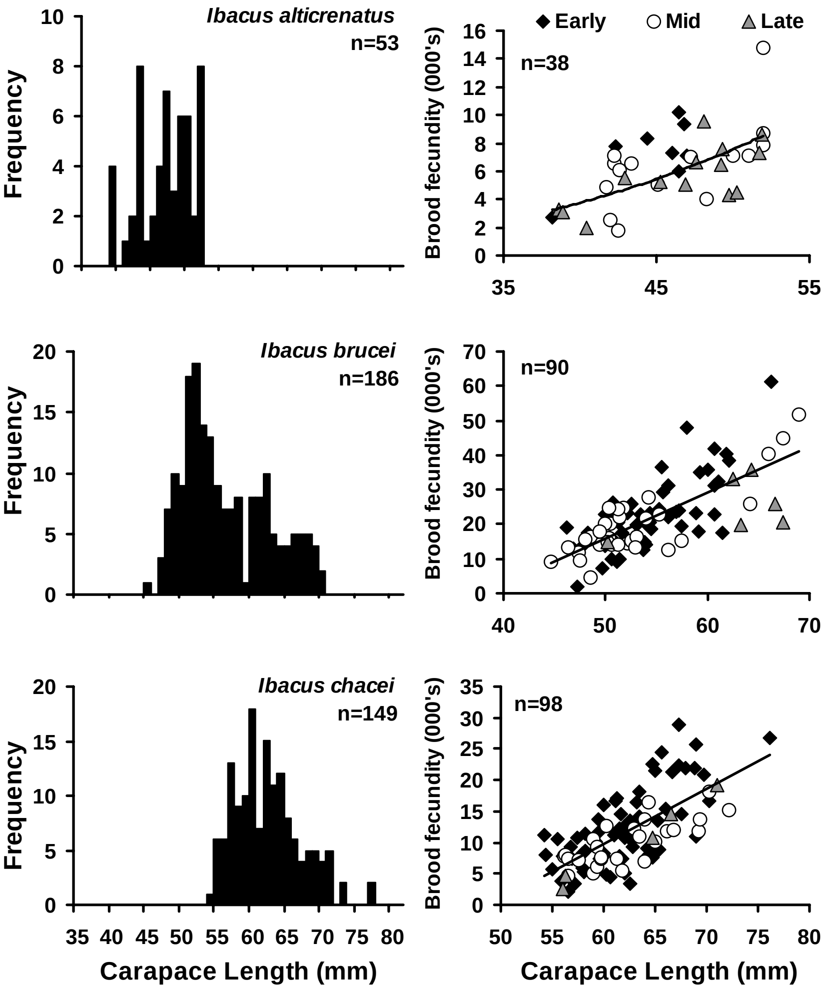


Figure 17.4.4. Size-frequency distributions of ovigerous females and scatterplot regressions of brood fecundity and carapace length for *Ibacus alticrenatus, Ibacus brucei* and *Ibacus chacei*. Note: y-axis ranges vary.

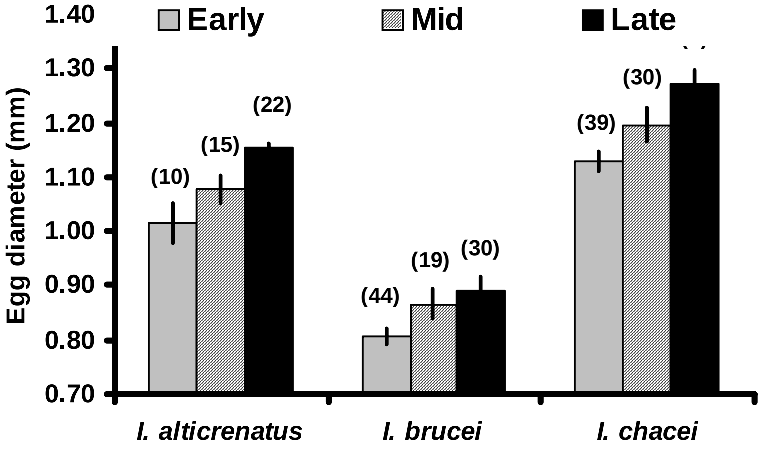


Figure 17.4.5. Comparisons of mean egg size (± 95% CI) with egg development for

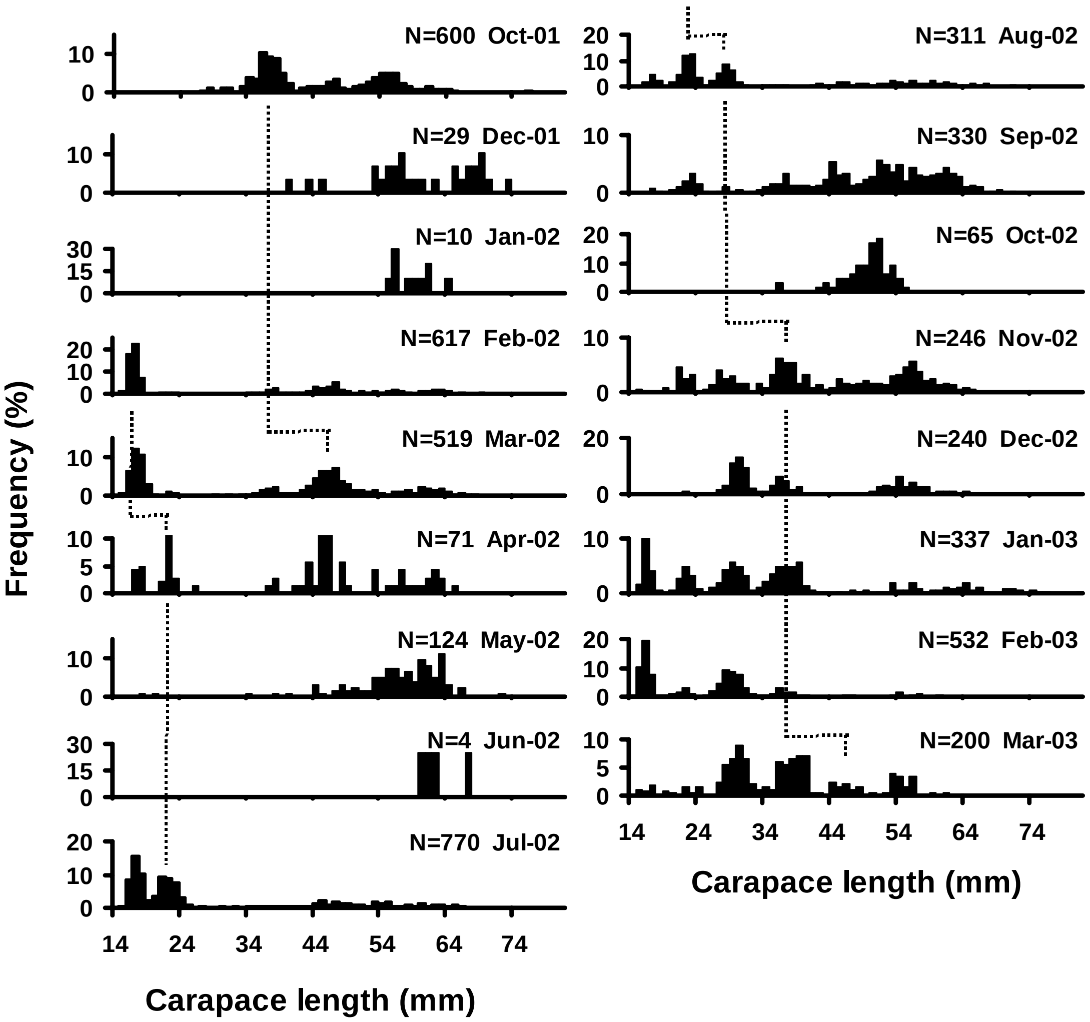


Figure 17.4.6. Monthly carapace length-frequency distributions of female *Ibacus chacei*. The dotted line outlines the suggested moulting pattern for individuals recruiting to the fishery in February. Note: y-axis ranges vary.

The percentage increase of each moult increment over its respective pre-moult CL was relatively large (range 24.1–31.8%) in small individuals (17–37 mm), but thereafter decreased with increasing animal size (Table 17.4.3). These growth increments, and the von Bertalanffy growth parameters detailed in Table 17.4.4, indicate that growth is relatively rapid in the first two years, but thereafter slows with females attaining larger sizes than males. The size at maturity is reached between 1.7 and 2 years post-settlement and individuals approach their maximum size within 5 to 7 years.

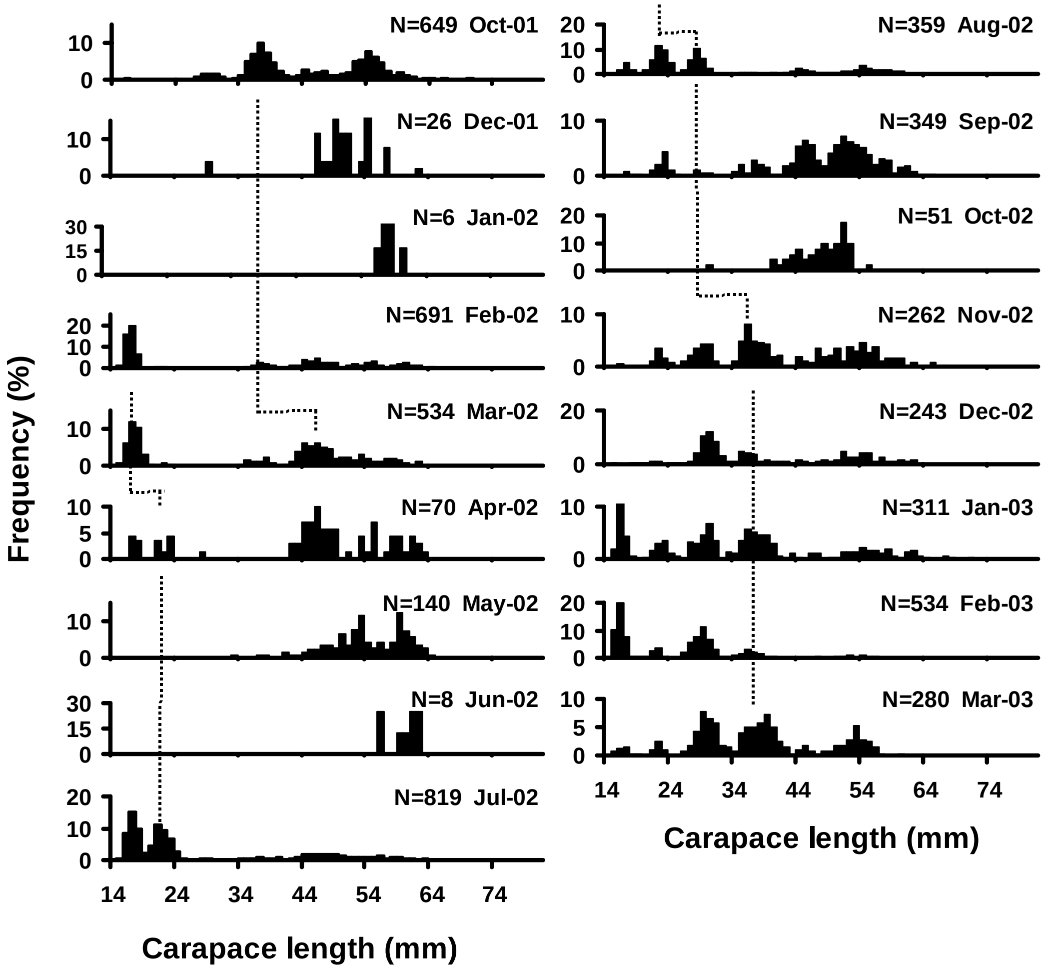


Figure 17.4.7. Monthly carapace length-frequency distributions for male *Ibacus chacei*. The dotted line outlines the suggested moulting pattern for individuals recruiting to the fishery in February. Note: y-axis ranges vary.

Ibacus brucei

Because reproductively mature females (stages 3–5) were present in all locations sampled, all data was pooled for clarity. Proportions of stage 3 and stage 4 females were highest in November, which also coincided with peak GSI values (data not shown). However, as samples could not be obtained from a full annual cycle (no samples were obtained between December and March), the proportions of these stages may reach higher values in summer/early autumn.

Ovigerous females were present from April–August inclusive and were most abundant in May. All ovigerous females possessed reproductively inactive ovaries (stage 2 or stage 5). Proportions of ovigerous females possessing early, mid- and late stage eggs were highest in April–May, June–July and July–August, respectively. Ovigerous females ranged in size from 44.6 – 69.7 mm CL (Figure 17.4.4). Brood fecundity ranged from 2049 to 61,339 eggs, was size dependent and best described by the linear regression, BF = 1.3354*CL –50.882 (r^2 = 0.52). Egg size ranged from 0.73 – 1.01 mm, was independent of lobster size and increased ($P < 0.001$; r^2 = 0.30) with egg stage (Figure 17.4.5). The mean number of eggs per gram body weight for ovigerous females was 246 ± 8 eggs g^{-1} (S.E.; range 40–425). No recently settled recruits were collected, however, a few small juveniles (20–27 mm CL) were collected in April, March and November.

Table 17.4.3. Moult increments of male and female *Ibacus chacei*. Pre-moult carapace lengths were determined from peak modal size classes indicated in Figure **17.4.1**.

Post-recruitment moult number	**Males** **Pre-moult CL (mm)**	**Moult increment (mm)**	**Per cent increase**	**Females** **Pre-moult CL (mm)**	**Moult increment (mm)**	**Per cent increase**
1	17	5	29.4	17	5	29.4
2	22	7	31.8	22	7	31.8
3	29	8	27.6	29	7	24.1
4	37	9	24.3	36	11	30.6
5	46	8	17.4	47	9	19.1
6	54	5	9.3	56	5	8.9

Table 17.4.4. Estimated von Bertalanffy growth parameters for *Ibacus chacei*

Sex	**L_∞ CL (mm)**	***k* (annual) (3 moults)**	**T_0 (annual) (3 moults)**	***k* (annual) (4 moults)**	**T_0 (annual) (4 moults)**
Females	81.0	0.45	-0.65	0.64	-0.38
Males	72.9	0.45	-0.61	0.74	-0.37

Ibacus alticrenatus

Due to highly variable sample sizes, seasonal reproductive activity could not be critically assessed. However, ovigerous females were present from April to September inclusive, with late stage ovigerous females present from June to September, and were most abundant in July. Ovigerous females ranged in size from 38.2–52.0 mm CL (Figure 17.4.4). Brood fecundity ranged from 1734–14,762 eggs, was size dependent and best described by the power regression, BF = $0.00005{*}CL^{3.1315}$ ($r^2 = 0.38$). Egg size ranged from 0.94–1.29 mm, was independent of lobster size and increased ($P < 0.001$; $r^2 = 0.56$) with egg stage (Figure 17.4.5). The mean number of eggs per gram body weight for ovigerous females was 121 ± 7 eggs g^{-1} (S.E.; range 44–208). Two small individuals (20 and 26 mm CL) were collected in January.

17.5 DISCUSSION

Spatial variation in the reproductive output of *I. chacei* (Figure 17.4.2) strongly suggests that geographical location (i.e., latitude) has a marked influence on their reproductive activity, with the southern boundary of vitellogenesis occurring between 26 and 27° S. This is consistent with previous studies on *I. chacei* in NSW waters (between 29 and 30° S) where researchers failed to find reproductively active animals (Stewart et al., 1997). Moreover, Stewart and Kennelly (1998) demonstrated that *I. chacei* undertook long northern migrations with individuals capable of travelling 310 km in 655 days. Collectively these findings indicate that *I. chacei* migrate to spawn with larvae being distributed southwards via the East Australian current.

Seasonal changes in the proportion of ovigerous females, GSI and ovarian development indicate that *I. chacei* displays an annual cycle of reproduction with oviposition occurring from late June to December. Furthermore, as ovigerous females are also found with mature and maturing ovaries, it is likely that some individuals spawn more than once in the same spawning season. Successive spawning within each season has been reported for several spiny lobsters (Briones-Fourzan and Lozano-Alvarez, 1992; Plaut, 1993; Chubb, 1994; Minagawa, 1997) and is also believed to occur in the scyllarids, *T. orientalis*, *T. indicus* (Jones, 1988), *S. latus* (Spanier and Lavalli, 1998), *S. nodifer* and *Scyllarus depressus* (Smith, 1881) (Lyons, 1970). Lipcius (1985) suggested that large spiny lobsters initiated egg production earlier and produced two broods in a spawning season, whereas younger individuals moult first, mature later and produce only one brood per season. However, as successive ovarian maturation in *I. chacei* was observed across a broad size range (55.8–72.2 mm), the production of multiple broods is more likely to be related to the duration of an individual's moult interval and the timing of the onset and duration of vitellogenesis.

Although seasonal reproductive data for *I. brucei* were incomplete, the seasonal occurrence of ovigerous females, GSI profiles and ovarian maturation proportions indicated that the species also had an annual cycle of reproduction. However, in contrast to *I. chacei*, reproductive activity was not geographically restricted with oviposition and hatching occurring earlier and predominantly over a shorter period. Furthermore, there was no supporting evidence to suggest that the species produces multiple broods within each season. Similarly, all ovigerous *I. alticrenatus* possessed reproductively inactive ovaries (stages 2 and 5) and reproductive activity was not geographically restricted. Ovigerous *I. alticrenatus* have been reported to occur along the eastern Australian coast from New South Wales to Tasmania between April and October (Holthuis, 1991; Brown and Holthuis, 1998). This study has now extended the known geographical range of reproductive activity in *I. alticrenatus*.

Our results indicate that brood fecundity is size dependent in all three species and that *I. alticrenatus* can carry approximately 1700–14,800 eggs, *I. brucei* can carry 2000–61,300 eggs and *I. chacei* can carry 2100–28,800 eggs. Stewart and Kennelly (1997) characterised the brood fecundity-carapace length (BF-CL) relationship of *I. peronii* as strongly positive and linearly related to carapace length with brood size ranging from 5500 to 36,700. Interestingly, their BF-CL regression equation for *I. peronii* is virtually the same for *I. chacei*. Similar linear BF-CL relationships have been described for *T. orientalis* and *T. indicus* with estimated fecundities ranging from 15,600–54,700 and 3700–25,100 respectively (Jones, 1988). Although *I. brucei* also exhibited a linear BF-CL relationship, their smaller egg size resulted in a marked increase in fecundity. Other scyllarid lobsters that produce eggs of a similar size to *I. brucei*, such as *S. latus* and *S. squammosus*, possess fecundities ranging from 151,000–356,000 and 53,800–227,500 eggs respectively; however, the BF-animal size relationships in these species are best described by curvilinear relationships (Martins, 1985; DeMartini and Williams, 2001). Similarly, the BF of *I. alticrenatus* was also best described by a curvilinear BF-CL relationship, but as this species is quite small and produces a relatively large egg its fecundity is comparatively lower. This highlights that the egg-carrying capacity of scyllarid lobsters, like palinurid lobsters, is highly variable and although all produce eggs as a positive function of animal size, the exact shape of the relationship (e.g., linear, curvilinear) varies among species.

Significant reductions in brood size can be caused by several factors such as egg losses during ovipositioning, poor fertilisation, aborted development, parasitism, maternal and external predation and mechanical loss due to abrasion with the substrate or by dislodgement during trawl capture (Kuris, 1991; Mori et al., 1998). Egg losses during incubation can have marked effects on BF-CL relationships and many researchers use only early stage eggs to avoid this problem; however, this can artificially elevate fecundity estimates. Alternatively, the use of late stage eggs is difficult as eggs are easily ruptured, which makes accurate estimates of fecundity difficult. In the present study we chose to use all stages and present an overall BF-CL relationship, as there were insufficient numbers of each egg stage to assess the effect of development stage on BF. However, there was a general tendency for individuals with mid- and late stage eggs to possess lower brood fecundities than similar sized individuals with early stage eggs, indicating that some egg losses are occurring during the incubation period. The mean monthly egg loss of ovigerous *Nephrops norvegicus* (Linnaeus, 1758) is estimated at approximately 10% with an overall mean egg loss from oocyte to hatching of 71.5% (Mori et al., 1998). Significant egg losses of 30–50% are also known to occur in *Homarus* spp. (Talbot, 1991). However, as both of these species possess prolonged incubation periods (> 6 months), their broods are highly susceptible to egg loss. Currently there is no detailed information on egg losses during the incubation period in scyllarid lobsters.

The seasonal development of eggs suggests that the egg incubation period in *Ibacus* spp. requires two to four months. Stewart et al., (1997) reported an incubation period of three to four months in captive *I. peronii;* however, *T. orientalis* eggs require only 40 days to hatch (Jones, 1988) while the incubation period for *S. latus* is three to eight weeks (Martins, 1985; Spanier and Lavalli, 1998). Although egg incubation periods are temperature dependent, the duration of the incubation period has marked implications on the life history strategy of a species. For example, species with short egg incubation periods typically exhibit higher fecundities and brood frequencies, produce smaller eggs, experience lower levels of egg loss and have a longer larval phase than species with long egg incubation periods. Contrasts in fecundity, egg size, egg incubation periods, and larval duration in lobsters are informative as they provide insights into the mechanisms each species utilises in order to optimise recruitment within their particular environment. Pollock and Melville-Smith (1993) suggested that the higher fecundities and smaller eggs of shallow water spiny lobsters and crabs over deepwater species resulted through evolutionary pressures of higher rates of mortality of larval and juvenile stages in coastal waters where predation pressures are higher. In contrast, several scyllarid studies suggest that the opposing fecundity-egg size tradeoffs between coastal (typically low fecundity species with large eggs) and oceanic (typically higher fecundity species with small eggs) scyllarids reflect the higher mortality rates of larvae in the open ocean due to low larval retention (Stewart and Kennelly, 1997; DeMartini and Williams, 2001).

In the present study, the majority of juvenile *I. chacei* were obtained off Mooloolaba, in waters 80–100 m deep, and were present over a prolonged period (Feb–Aug). The appearance of late stage ovigerous females (close to hatching) in August–September and large numbers of juveniles (14–20 mm CL) in February indicate that *I. chacei* recruit to the trawl fishery five to six months after hatching. Studies on the larval development of *Ibacus* spp. indicate that members of this genus undergo six to eight phyllosoma stages over two to four months before metamorphosing into a post-larval stage (Ritz and Thomas, 1973; Takahashi and Saisho, 1978; Phillips et al., 1981; Atkinson and Boustead, 1982). Ritz and Thomas (1973) showed that transitional postlarvae of *I. peronii* (= puerulus in palinurids) measuring 11.4 mm CL moulted into a lightly pigmented juvenile measuring 12.5 mm CL after 22 days, and after the next moult some 40 days later were fully pigmented and measured 17.2 mm CL. Although juvenile *I. chacei* were present over a prolonged period (Figure 17.4.6 and Figure 17.4.7) very few juvenile *I. brucei* or *I. alticrenatus* were collected. Brown and Holthuis (1998) reported juveniles of *I. alticrenatus* in 400 and 686 m in November and October, respectively, and juvenile *I. brucei* in 138 and 210 m in November and December, respectively. This suggests that *I. alticrenatus* and *I. brucei* settle earlier and in deeper water than *I. chacei*.

As lobster growth is a discontinuous process, growth is best described by two factors: the inter-moult period and moult increment. In the present study moult increments for *I. chacei* were determined from pooled length frequency distributions whereas moulting frequencies were estimated from monthly length-frequency distributions. These results showed that early juvenile growth in *I. chacei* is characterised by relatively large moult increments of 24 to 32% of their pre-moult size; however, in larger individuals the relative size of the moult increment decreases. Our results for *I. chacei* indicate that although females attain larger sizes than males, the moult increments between sexes were very similar. This implies that females either possess a shorter inter-moult period or live longer than males. Stewart and Kennelly (2000) indicated that female *I. peronii* grew larger and faster than males and suggested that females moulted more frequently, whereas in *I. chacei* no differences in growth between the sexes were detected. However, as their description of growth in *I. chacei* was based on a small number of recaptures (9 males and 26 females) from a population of reproductively inactive individuals at the southern end of the species distribution, their results may not accurately describe growth patterns of the entire population. Although the von Bertalanffy growth function may not adequately describe growth of crustaceans (Breen, 1994; Stewart and Kennelly, 2000), it is still useful in providing growth parameter estimates when other growth models are not available and for comparisons with previous studies. The growth parameters of *I. chacei* estimated in the present study indicate that females reach sexual maturity between 1.7–2 years post-settlement and that they approach their maximum size within 5–7 years. Similarly, the age of maturity of *I. peronii* was estimated at approximately two years after settling as postlarvae with their $L_{\max}$ being reached between 5 and 18 years (Stewart and Kennelly, 2000).

Very few authors have commented on the presence and structure of spermatophoric masses within the Scyllaridae family, which has produced speculation that fertilisation is internal (Lyons, 1970). Berry and Heydorn (1970) indicated that in spiny lobsters there are three basic types of spermatophoric masses: a granular and putty like spermatophoric mass that hardens in seawater; a gelatinous spermatophore that disintegrates in seawater; and a gelatinous spermatophoric mass, which does not disintegrate in seawater. Both *Parribacus antarcticus* (Lund, 1793) and a *Scyllarus* spp. have been reported to possess a hard persistent spermatophoric mass (Lyons, 1970; Jones, 1988), whereas *I. peronii* (Stewart et al., 1997), *S. latus* (Martins, 1985; Stewart et al., 1997) and *T. orientalis* (personal observation) possess a non-disintegrating gelatinous spermatophore. In the present study, the occurrence of ovigerous females carrying spermatophoric masses was relatively rare and only observed in “hard-shelled” *I. chacei* carrying early stage eggs. This suggests that moulting is not a prerequisite for mating in *I. chacei* and that the duration between mating and ovipositioning is short. Similar findings have also been reported for *S.*

nodifer where captive individuals extruded their eggs within 24–48 hours after mating (Hardwick and Cline, 1990). Therefore, it would appear that the mechanisms of mating and egg fertilisation in scyllarid lobsters is just as variable as those described for palinurid lobsters (Berry and Heydorn, 1970; Aiken and Waddy, 1980).

The results of this study have provided fisheries managers with detailed information on the size at maturity of Queensland's commercially important *Ibacus* spp. and highlighted that the current management strategies are resulting in an unnecessary reduction of catches of *I. brucei* and *I. alticrenatus*, while also allowing the retention of immature *I. chacei*. Furthermore, as *Ibacus* spp. are easily distinguished by morphological features, species-specific MLS could be implemented. MLS should be set to ensure lobsters breed at least once before recruitment to the fishery or at least at 50% maturity levels. In this case a MLS of approximately 80 mm CW for *I. brucei* (CL = 48.5 mm) and *I. alticrenatus* (CL = 50.4 mm) and 105 mm CW for *I. chacei* (CL = 57.1 mm) could be implemented, as this would allow fishers to retain marketable individuals while also maintaining the protection of immature stocks.

17.6 REFERENCES

Aiken, D. E., 1980. Moulting and growth. In: Cobb J.S., Phillips, B.F. (eds.) The biology and management of lobsters. Academic Press, New York. pp. 91–163.

Aiken, D. E., Waddy, S. L., 1980. Reproductive biology. In: Cobb J.S., Phillips, B.F. (eds.) The biology and management of lobsters.Academic Press, New York. 215–276.

Atkinson, J. M., Boustead, N. C., 1982. The complete larval development of the scyllarid lobster *Ibacus alticrenatus* (Bate, 1888) in New Zealand waters. Crustaceana 42: 275–287.

Berry, P. F., Heydorn, A. E. F., 1970. A comparison of the spermatophoric masses and mechanisms of fertilization in southern African spiny lobsters (Palinuridae). Investigational Report of the Oceanographic Research Institute. 1–18.

Breen, P. A., 1994. Population dynamics and stock assessment of lobsters: A review. Crustaceana 67: 239–255.

Briones-Fourzan, P., Lozano-Alvarez, E., 1992. Aspects of the reproduction of *Panulirus inflatus* (Bouvier) and *P. gracilis* (Streets) (Decapoda: Palinuridae) from the Pacific coast of Mexico. J. Crustacean Biology 12: 41–50.

Brown, D. E., Holthuis, L. B., 1998. The Australian species of the genus *Ibacus* (Crustacea: Decapoda: Scyllaridae), with the description of a new species and addition of new records. Zoologische Mededelingen 72: 113–141.

Chubb, C. F., 1994. Reproductive biology: Issues for management. In: Phillips, B. F., Cobb, J. S., Kittaka, J., (eds.) Spiny Lobster Management. Blackwell Scientific Publications, London. 181–212.

Courtney, A. J., 2002. Research results on the effects of bycatch reduction devices in the eastern king prawn fishery. Queensland Fisherman 20: 20–23.

Courtney, A. J., Campbell, M., 2003. Square mesh BRDs show good results. Queensland Fisherman 21: 32–35.

Courtney, A. J., Cosgrove, M. G., Die, D. J., 2001. Population dynamics of scyllarid lobsters of the genus *Thenus* spp. on the Queensland (Australia) east coast. I. Assessing the effects of tagging. Fisheries Research 53: 251–261.

DeMartini, E. E., Williams, H. A., 2001. Fecundity and egg size of *Scyllarides squammosus* (Decapoda: Scyllaridae) at Maro Reef, northwestern Hawaiian Islands. J. Crustacean Biology 21: 891–896.

GenStat 6, 2002. GenStat, 6th Edition. Lawes Agricultural Trust.

Hardwick, C. W., Cline, G. B., 1990. Reproductive status, sex ratios and morphometrics of the slipper lobster *Scyllarides nodifer* (Stimpson) (Decapoda: Scyllaridae) in the northeastern Gulf of Mexico. Northeast Gulf Science 11: 131–136.

Hill, B. J., Wassenberg, T. J., 1990. Fate of discards from prawn trawlers in Torres Strait. Australian Journal of Marine and Freshwater Research 41: 53–64.

Holthuis, L. B., 1991. Marine lobsters of the world. An annotated and illustrated catalogue of the species of interest to fisheries known to date. FAO species catalogue. Vol 13. FAO (UN) Rome.

Hossain, M. A., 1975. On the squat lobster, *Thenus orientalis* (Lund) off Visakhapatnam (Bay of Bengal). Current Science 44: 161–162.

Jones, C. M., 1988. The biology and behaviour of bay lobsters, *Thenus* spp. (Decapoda: Scylaridae), in northern Queensland, Australia. PhD thesis, University of Queensland.

Kaiola, P. J., Williams, M. J., Stewart, P. C., Reichelt, R. E., McNee, A., Grieve, C., 1993. Australian fisheries resources. Bureau of Resource Sciences and Fisheries Research and Development Corporation, Canberra.

Kuris, A.M., 1991. A review of patterns and causes of crustacean brood mortality. In: Wenner, A. M., Kuris, A.M., (eds.) Crustacean Issues, Vol 7: Crustacean Egg Production. Balkema, Rotterdam. 117-142.

Lipcius, R. N., 1985. Size-dependent reproduction and moulting in spiny lobsters and other long-lived decapods. In: Wenner, A. M., (ed.) Crustacean Issues, Vol 3: Factors in Adult Growth. Balkema, Rotterdam. 129–148.

Lyons, W. G., 1970. Scyllarid lobsters (Crustacea, Decapoda). Memoirs of the hourglass cruises. Marine Research Laboratory, Florida Department of Natural Resources 1: 1–74.

Marinovic, B., Lemmens, J. W. T. J., Knott, B., 1994. Larval development of *Ibacus peronii* (Leach) (Decapoda: Scyllaridae) under laboratory conditions. J. Crus. Biol. 14: 80–96.

Martins, H. R., 1985. Biological studies of the exploited stock of the Mediterranean locust lobster *Scyllarides latus* (Latreille, 1803) (Decapoda: Scyllaridae) in the Azores. J. Crus. Biol. 5: 294–305.

Minagawa, M., 1997. Reproductive cycle and size-dependent spawning of female spiny lobsters (*Panulirus japonicus*) off Oshima Island, Tokyo, Japan. Mar. Freshw. Res. 48: 869–874.

Mori, M., Biagi, F., De Ranieri, S., 1998. Fecundity and egg loss during incubation in Norway lobster (*Nephrops norvegicus*) in the North Tyrrhenian Sea. J. Nat. Hist. 32: 1641–1650.

Phillips, B. F., Brown, P. A., Rimmer, D. W., Braine, S. J., 1981. Description, distribution and abundance of late larval stages of the Scyllaridae (slipper lobsters) in the South-Eastern Indian Ocean. Aust. J. Mar. Freshw. Res.32: 417–437.

Plaut, I., 1993. Sexual maturity, reproductive season and fecundity of the spiny lobster *Panulirus penicillatus* from the Gulf of Eilat (Aqaba), Red Sea. Aust. J. Mar. Freshw. Res. 44: 527–535.

Pollock, D.E., Melville-Smith, R., 1993. Decapod life histories and reproductive dynamics in relation to oceanography off Southern Africa. South African J. Mar. Sc. 13: 205-212.

Quackenbush, L. S., 1994. Lobster reproduction: A review. Crustaceana 66: 82–94.

Ritz, D. A., Thomas, L. R., 1973. The larval and post-larval stages of *Ibacus peronii* (Leach) (Decapoda, Reptantia, Scyllaridae). Crustaceana 24: 5–16.

Spanier, E., Lavalli, K. L., 1998. Natural history of *Scyllarides latus* (Crustacea: Decapoda): a review of the contemporary biological knowledge of the Mediterranean slipper lobster. J. Nat. Hist. 32: 1769–1786.

Stewart, J., Kennelly, S. J., 1997. Fecundity and egg size of the Balmain bug *Ibacus peronii* (Leach, 1815) (Decapoda, Scyllaridae) off the east coast of Australia. Crustaceana 70: 191–197.

Stewart, J., Kennelly, S. J., 1998. Contrasting movements of two exploited scyllarid lobsters of the genus *Ibacus* off the east coast of Australia. Fish. Res. 36: 127–132.

Stewart, J., Kennelly, S. J., 2000. Growth of the scyllarid lobsters *Ibacus peronii* and *I. chacei.* Mar. Biol. 136: 921–930.

Stewart, J., Kennelly, S. J., Hoegh-Guldberg, O., 1997. Size at sexual maturity and the reproductive biology of two species of Scyllarid lobster from New South Wales and Victoria, Australia. Crustaceana 70: 344–367.

Takahashi, M., Saisho, T., 1978. The complete larval development of the Scyllarid lobster, *Ibacus ciliatus* (Von Siebold) and *Ibacus novemdentatus* (Gibbes) in the laboratory. Memoirs of the Faculty of Fisheries, Kagoshima University. 27: 305–353.

Talbot, P., 1991. Ovulation, attachment and retention of lobster eggs. In: Wenner, A. M., Kuris, A.M., (eds.) Crustacean Issues, Vol 7: Crustacean Egg Production. Balkema, Rotterdam. 9–18

Zhu, D., Li, S., Wang, G., 2001. Studies on some characteristics of the reproductive biology in the squat lobster *Thenus orientalis*. J. Trop. Oceanog. 20: 41–46.

18 Observations on the distribution, growth and reproductive biology of *Nemipterus theodorei* and *Nemipterus aurifilum* caught in the Queensland (Australia) East Coast Trawl Fishery

M. J. Campbell, D. P. Roy, J. A. Haddy and A. J. Courtney

18.1 ABSTRACT

This chapter examines the distribution and population dynamics of two species of nemipterid fish, *N. theodorei* and *N. aurifilum*, that make up the majority of the trawl-caught catch of "pinkies" in Queensland. Extremely little information has been published on these two species. *N. theodorei* is the main species contributing to landings and market value in Queensland, mainly because it is more abundant and the larger of the two species. Standard length-size class modes were 140 mm and 90 mm for *N. theodorei* and *N. aurifilum*, respectively. *N. theodorei* were more wide spread in their distribution and generally found in depths of less than 100 m, while *N. aurifilum* was found in depths greater than 100 m. Fifty per cent of females were found to be mature at 142 mm and 90 mm fork length, for *N. theodorei* and *N. aurifilum,* respectively. Preliminary estimates of the von Bertalanffy growth parameters were obtained for both species and sexes, based on otolith age readings and length-at-age analyses, but are likely to be affected by a lack of small/young sizes classes in the samples. Spawning for *N. theodorei* peaked in spring and summer, and was at a minimum in winter.

18.2 INTRODUCTION

In 1999, the Queensland Government passed legislation allowing trawl fishers operating in the Queensland East Coast Trawl Fishery to retain and market fishes belonging to the Nemipteridae family. The Management Plan [*Fisheries (East Coast Trawl) Management Plan 1999*] specifies that fishers can be in possession of up to 198 litres of nemipterids, of any size or species. This catch limit was not based on any quantitative assessment of the stock, but rather on the equivalent volume of a certain number of lug baskets. Processors generally only market individuals that are 200 mm in length or longer.

Previous observations on the bycatch from the fishery indicated that the nemipterid catches were largely comprised of two species, *Nemipterus theodorei* and *Nemipterus aurifilum*. The review of nemipterids undertaken as part of Objective 4 (Chapter 12, section 12.1.8) revealed that there had been very little published on the biology and population dynamics of these two species. This chapter presents preliminary observations on the distribution, biology and population dynamics of *N. theodorei* and *N. aurifilum* from the Queensland east coast, with the intention of providing management advice.

18.3 MATERIALS AND METHODS

18.3.1 Sampling methods

Samples of nemipterids were obtained throughout the project from the research charters' bycatch samples and from the opportunistic bycatch samples. In addition, a fishers (Mr Tony Sterling) agreed to provide samples to the project on a regular basis from April 2000 to November 2002. All samples were obtained from areas between Shoalwater Bay (22°30’ S) and Southport (28° S), which reflected the distribution of reported commercial landings based on logbook data (Figure 18.3.1).

All samples had been frozen and were thawed in the laboratory before obtaining biological data. Standard length measures to the nearest 5 mm were obtained for every individual and used for length-frequency analysis, while standard length measures to the nearest 1 mm were used to derive length-weight relationships and growth rates. Wet weight was recorded to the nearest 0.1 g using electronic scales. Non-linear regression coefficients for the length-weight relationships were estimated using the function nlinfit from MATLAB® using finite difference approximation algorithms. 95% confidence intervals were calculated using the MATLAB function nlpredci.

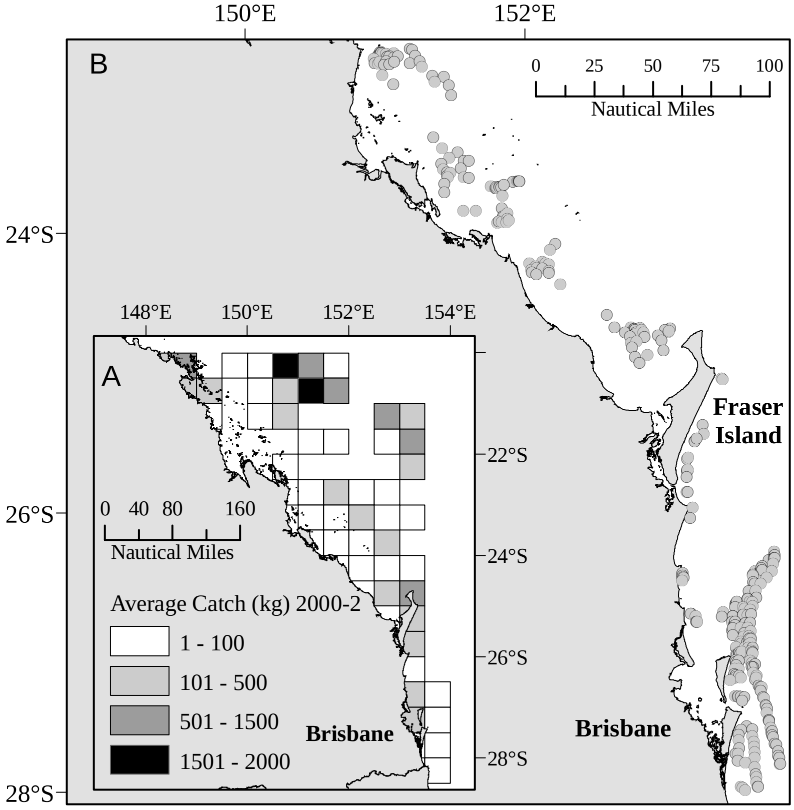


Figure 18.3.1. The reported commercial landings of nemipterids (2000–2002) from the Queensland East Coast Trawl Fishery and trawl locations from the opportunistic sampling and research charters where samples were collected

18.3.2 Ageing and growth

Otoliths were removed from fish, placed in labelled vials and forwarded to Mr Corey Green from the Victorian Department of Natural Resources and Environment Central Ageing Facility for age determination (see details of the otolith sectioning and ageing methods in Appendix 8, “Age estimates of two species of threadfin bream: *Nemipterus theodorei* and *Nemipterus aurifilum*”).

The von Bertalanffy growth equation [$L_t = L_\infty(1-e^{-k(t-to)})$] was fitted to the length-at-age data for females and males, where L_∞ is the mean asymptotic length predicted by the equation, k is the growth coefficient, and t_o is the hypothetical age at which fish would have zero length. It was assumed that the lengths-at-age were normally distributed around the values predicted from the equation and that the variance of this distribution was constant for each sex over all ages. Growth equations were fitted to the observed length-at-age data by estimating the growth parameters with the SOLVER routine in Microsoft Excel and minimising the sum of squares.

18.3.3 Reproductive biology

Testes and ovaries were dissected from the fish that were provided each month by the commercial fisher and weighed to the nearest 0.01 g. Ovaries were staged macroscopically, based on a modification of the criteria used by Haddy and Pankhurst (1998) (Table 18.3.1). Gonadosomatic indices (GSIs) were determined using the equation:

$$\mathrm{GSI} = W_1/W_2*100$$

where W_1 = weight of wet gonad; and W_2 = weight of the whole fish.

Table 18.3.1. Criteria for macroscopic classification of *Nemipterus* spp. ovaries

Stage	Classification	Macroscopic appearance
1	Immature	Ovary small clear threads
2	Regressed	Ovary enlarging but still clear
3	Vitellogenic	Ovary enlarging with opaque oocytes visible through epithelium
4	Hydrated	Ovary enlarged with opaque and hydrated oocytes visible through epithelium
5	Ovulated	Eggs in the oviduct can be extruded with gentle pressure
6	Spent	Ovary flaccid and bloody

18.4 RESULTS

Table 18.4.1 summarises the numbers of individuals used in the respective analyses.

Table 18.4.1. Sample sizes (number of fish) contributing to biological analyses conducted on *N. theodorei* and *N. aurifilum*

Species	Sex	Length-frequency analysis	Length-weight relationship	Ageing and growth rates	Gonado-somatic index
N. theodorei	M	4739	174	187	642
	F		129	161	264
N. aurifilum	M	1277	162	104	128
	F		213	97	207

There was a marked distinction in the distribution of the two species. *N. theodorei* were generally found in depths less than 100 m while *N. aurifilum* was found in depths greater than 100 m (Table 18.4.2). *N. theodorei* were more widespread in distribution with individuals occurring in 49.2% of trawls and distributed from Yeppoon in Central Queensland south to the Queensland/NSW border. *N. aurifilum* was caught in only 23.5% of trawls and restricted to depths greater than 75 m. *N. aurifilum* occurs in the deepwater eastern king prawn fishery, while *N. theodorei* occurs in both the shallow water eastern king prawn fishery and the scallop fishery.

Table 18.4.2. Summary of distribution data for *N. theodorei* and *N. aurifilum* based on the number of individuals caught during research charters and opportunistic sampling aboard commercial vessels. Sample sizes for *N. theodorei* and *N. aurifilum* were 3356 and 876 respectively. Standard errors in brackets.

Species	**Size range and mean length (mm)**	**Depth range and mean (m)**	**Latitudinal range**	**% Occurrence in trawl shots**	**Average catch rate (g/ha)**	**Depth of highest individual catch rate (m)**
N. theodorei	45 to 240 139.0 (0.5)	17 to 117 50.1 (3.43)	22º40.477 S to 27º59.200 S	49.2%	453.7 (40.6)	50
N. aurifilum	40 to 220 111.9 (1.7)	75 to 165 122.9 (2.4)	26º16.541 S to 27º47.570 S	23.5%	49.7 (8.6)	100

18.4.1 Length-frequency analyses

Figure 18.4.1 and Figure 18.4.2 show the length-frequency histograms for both *N. theodorei* and *N. aurifilum,* respectively. Very few small *N. theodorei* were caught particularly in size classes up to 120 mm. In contrast, a larger proportion of the smaller size classes were present in the catch of *N. aurifilum*. This may indicate that smaller individuals of *N. aurifilum* were present on the trawl grounds, while the fishery operates largely outside of areas that small or juvenile *N. theodorei* inhabit.

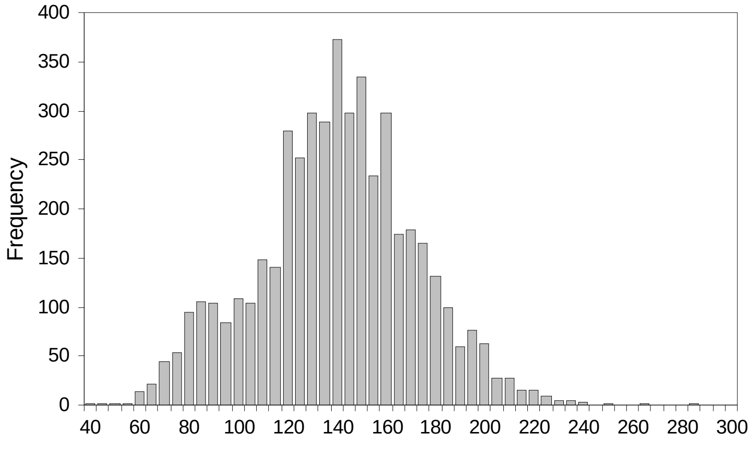


Figure 18.4.1. Length-frequency histogram for *N. theodorei* based on 4738 individuals obtained from trawl samples. Sexes pooled.

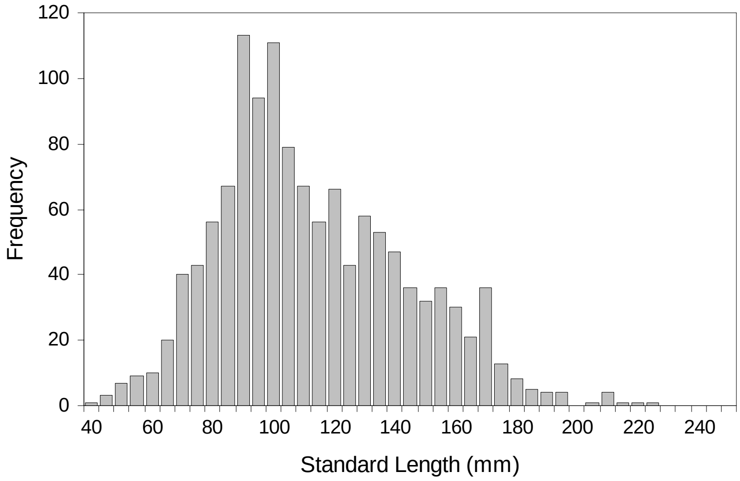


Figure 18.4.2. Length-frequency histogram for *N. aurifilum* based on 1276 individuals obtained from trawl samples. Sexes pooled.

18.4.2 Length-weight relationships

The relationship between standard length (SL) in mm and total wet weight (W) in g of each species was:

N. theodorei	Males	$W = 0.00004398\ SL^{2.8424}$
	Females	$W = 0.00001684\ SL^{3.0356}$
N. aurifilum	Males	$W = 0.00001964\ SL^{2.9857}$
	Females	$W = 0.00001107\ SL^{3.1054}$

The relationships are presented graphically in Figure 18.4.3, Figure 18.4.4, Figure 18.4.5 and Figure 18.4.6.

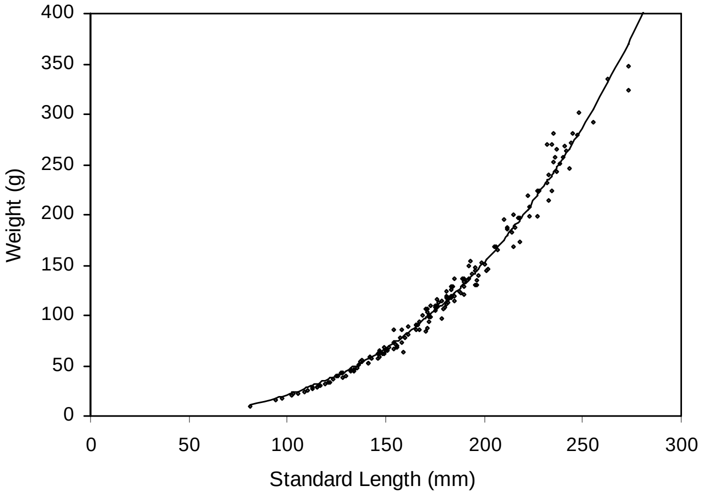


Figure 18.4.3 Length-weight relationship for male *N. theodorei*

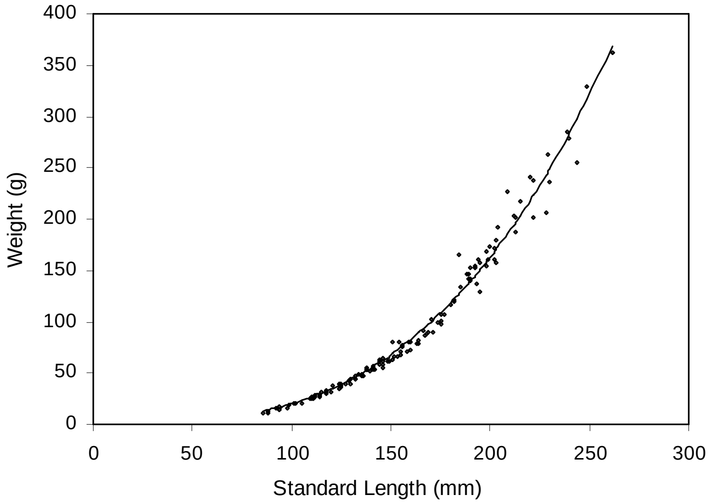


Figure 18.4.4. Length-weight relationship for female *N. theodorei*

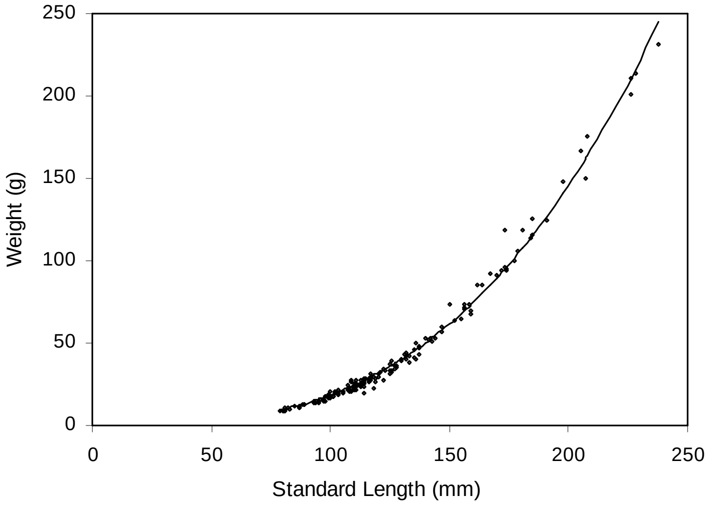


Figure 18.4.5. Length-weight relationship for male *N. aurifilum*

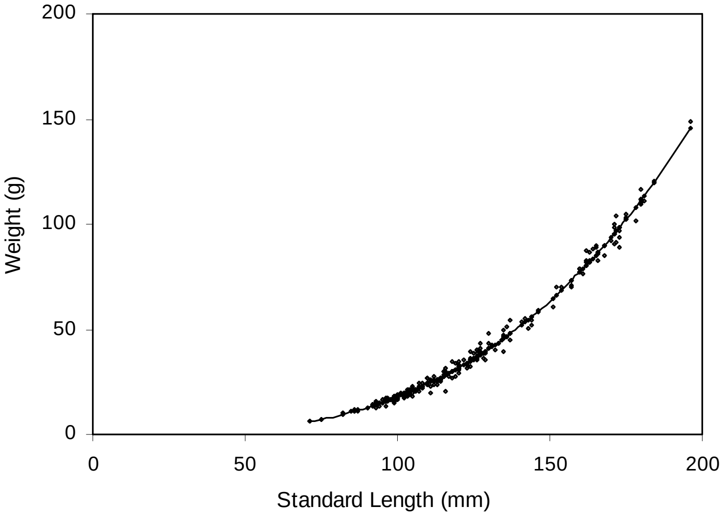


Figure 18.4.6. Length-weight relationship for female *N. aurifilum*

18.4.3 Age and growth

Estimates of the mean length-at-age, based on the ageing analyses undertaken at the Central Ageing Facility, are provided in Table 18.4.3. These data were used to estimate the growth parameters provided in Table 18.4.4. Because of the lack of small individuals in the length-frequency samples the von Bertalanffy model does not fit the data very well. The growth parameter estimates could be improved in future by including more of the smaller size classes and including their age estimates in the model fitting.

Table 18.4.3. Mean length (mm)-at-age for *N. theodorei* and *N. aurifilum* based individuals aged at the Central Ageing Facility. Methods for ageing are described in Appendix 8. Standard errors in brackets.

Species	**Sex**	**Adjusted Age (yrs)**				
		0	**1**	**2**	**3**	**4**
N. theodorei	Male	95.16 (2.49) n = 57	135.18 (3.41) n = 28	185.32 (2.59) n = 66	232.85 (2.29) n = 33	266.33 (15.38) n = 3
N. theodorei	Female	93.00 (2.23) n = 57	129.29 (2.79) n = 34	177.92 (2.83) n = 48	200.94 (5.06) n = 16	242.67 (5.36) n = 6
N. aurifilum	Male	88.68 (3.05) n = 41	129.34 (3.62) n = 38	175.05 (4.57) n = 19	204.17 (10.10) n = 6	-
N. aurifilum	Female	89.31 (3.20) n = 39	129.18 (3.60) n = 38	163.94 (3.89) n = 16	178.5 (8.05) n = 4	-

Table 18.4.4. von Bertalanffy growth parameter estimates for male and female *N. theodorei* and *N. aurifilum*

Species	**Sex**	**n**	**K**	**L∞**	**t_o**
N. theodorei	Male	187	0.10	614.8	-1.7
N. theodorei	Female	161	0.10	541.3	-1.9
N. aurifilum	Male	104	0.08	682.9	-1.8
N. aurifilum	Female	97	0.36	228.4	-1.4

18.4.4 Reproductive biology

Fifty per cent of female *N. theodorei* were found to have mature ovaries at 142 mm fork length, while 50% of female *N. aurifilum* were mature at 90 mm fork length.

The samples that were provided by the commercial fisher and used to examine seasonal variation in reproduction were limited to *N. theodorei*, mainly because he generally only retained *N. theodorei* which is the larger and more abundant of the two species. As such, no seasonal information on reproductive activity is provided for *N. aurifilum*.

The seasonal variation in ovary stages for female *N. theodorei* between November 2001 and December 2002 is provided in Figure 18.4.7 and suggests that spawning probably occurs over spring and summer. The incidence of stage 3 vitellogenic ovaries peaked from December to February and was at a minimum between June and

August. This seasonal trend is supported by the variation in GSIs (Figure 18.4.8 and Figure 18.4.9). Female GSIs peaked in spring (October to November) and were at a minimum in winter (July to August).

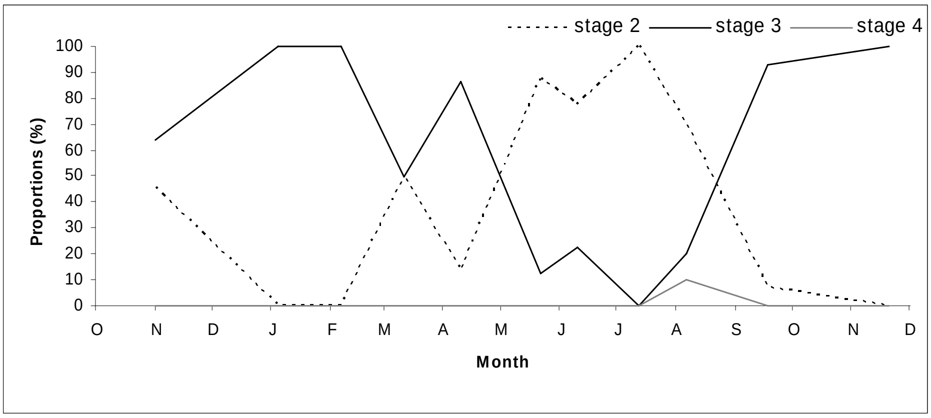


Figure 18.4.7. Changes in gonad stage for female *N. theodorei* between November 2001 and December 2002 based on classifications provided in Table 18.3.1

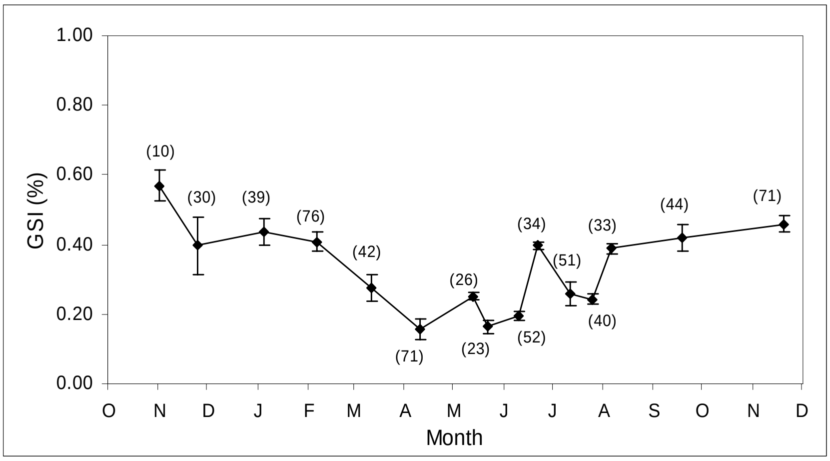


Figure 18.4.8. Gonadosomatic index for male *N. theodorei* between November 2001 and November 2002. Numbers in brackets indicate sample size

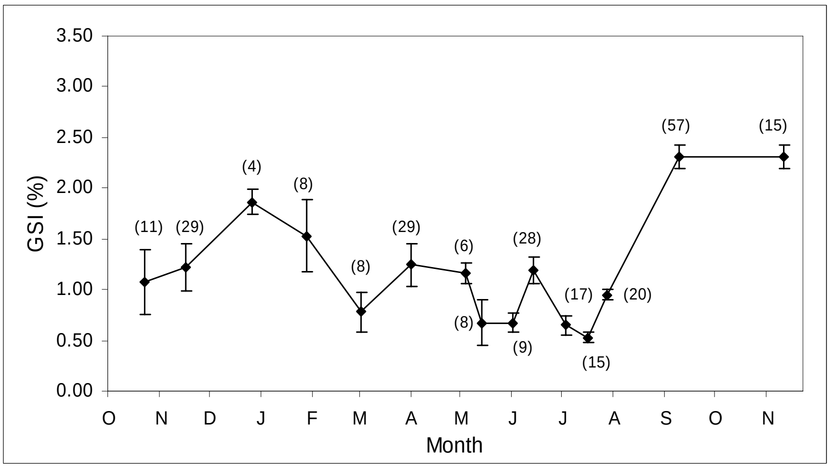


Figure 18.4.9. Gonadosomatic index for female *N. theodorei* between November 2001 and November 2002. Numbers in brackets indicate sample size

18.5 DISCUSSION

Very little is known about the biology and population dynamics of *N. theodorei* and *N. aurifilum* and the results presented here represent a significant contribution towards understanding and managing these species. The results indicate that *N. theodorei* is likely to be the main species contributing to the landings and market value for pinkies in Queensland because its length-frequency distribution (Figure 18.4.1 and Figure 18.4.2) indicates that it is the larger and more abundant of the two species, and because processors generally only resell individuals larger than about 200 mm. Model sizes (sexes pooled) for *N. theodorei* and *N. aurifilum* were about 140 mm and 90 mm, respectively.

There were distinct differences in the distribution of the two species. *N. theodorei* was generally obtained from depths less than 100 m, while *N. aurifilum* was generally found in greater depths. *N. theodorei* was also more widespread than *N. aurifilum.* Growth analyses indicate that males grow to larger maximum sizes than females, for both species. Maximum ages for *N. theodorei* and *N. aurifilum* were about four years and three years, respectively. Growth parameter estimates could be improved in future by including more small size classes.

There was marked seasonal variation in spawning for *N. theodorei*, with most egg production occurring in spring and summer. Reproductive activity was at a minimum in winter. Future reproductive studies would benefit from having access to fresh and unfrozen samples, as freezing tended to make staging of ovaries and testes difficult.

18.5.1 Management advice

N. theodorei and *N. aurifilum* appear to be abundant in south-east Queensland coastal waters. They have relatively short life spans, in the order of 3–4 years and reproduce at relatively small size classes; 50% of females were mature at 142 and 90 mm fork length for *N. theodorei* and *N. aurifilum*, respectively. It is difficult to provide specific management recommendations for these species. For example, minimum legal sizes would have little impact because most, if not all, undersized individuals would die after being trawled before being returned to the water, or shortly after. Similarly, total allowable catches (TACs) would not adequately limit or control the level of exploitation because many more individuals would continue to die in incidental catches while targeting prawns and scallops, after the TAC had been reached. The level of fishing mortality applied to the stocks is likely to be directly related to the level of trawl fishing effort applied to the prawns and scallops. Seasonal or spatial closures also appear to be inappropriate because they would impact upon catches of the main target species. If the level of fishing mortality applied to *N. theodorei* and *N. aurifilum* is considered to be excessive, then the fusiform body shape of the fish suggests radial escape section BRDs may be an appropriate method for lowering mortality.

18.6 REFERENCES

Haddy, J.A. and Pankhurst, N.W., 1998. Annual change in reproductive condition and plasma concentrations of sex steroids in black bream, *Acanthopagrus butcheri* (Munro) (Sparidae). Mar. Freshwat. Res. 49, 389-397.

19 Benefits and adoption

The Queensland East Coast Trawl Fishery, which is comprised of the largest prawn trawl fleet in Australia, benefits from the research because stakeholders, including fishers, management agencies, conservation groups and the public now have access to robust objective information on a) the bycatch composition in each of the major sectors, b) the performance of BRDs that are being used by fishers, and c) the potential reductions in bycatch that could be achieved, based on research charters.

Stakeholders are in a much more informed position to a) assess how well bycatch reduction initiatives (i.e., the implementation of TEDs and BRDs) have performed since being introduced in 2000, and b) plan future bycatch reduction initiatives.

The research charters provided stakeholders with information on the expected reductions in a) total bycatch and b) individual bycatch species, should fishers decide to use those devices that were tested. For example, the research charter results presented in Chapter 5 showed fishers that they could reduce their incidental catch rate of stout whiting *S. robusta* in the shallow water eastern king prawn fishery by a mean of 57%, compared to a standard net, by using a radial escape section BRD with a TED (Table 5.4.2). In the saucer scallop fishery we demonstrated that total bycatch rates could be reduced by a mean of 77% by using a square mesh codend BRD with a TED, compared to a standard net (Table 7.4.1). Importantly this was achieved with no loss of legal sized scallops, and a 63% reduction in the catch rate of undersized scallops.

Any reduction in bycatch rate, and the subsequent reduction in incidental fishing mortality on bycatch species, is likely to be deemed as a “benefit” to coastal ecosystems and biodiversity. This is difficult to quantify, but as an example, if all scallop fishery operators adopted the combination of TED and square mesh codend BRD trialled in Chapter 7, a reduction in bycatch of over 10,000 t could be achieved annually, compared to pre-TED and pre-BRD levels. Such benefits are likely to be highly valued by society.

Although not quantified by the project, the large reduction in bycatch rates achieved in the scallop fishery charter would almost certainly reduce vessel fuel consumption. If the amount of bycatch in the net is reduced by 77%, then the drag on the nets would most likely be reduced, thus reducing fuel costs and benefiting fishers. Similar benefits could be applied to deepwater eastern king prawn fishers who choose to use square mesh codends. Another benefit from the scallop fishery charter is the reduction in catch rate of undersized scallops. By reducing the number of undersized scallops that are retained in the net, brought to the surface, dropped onto the sorting tray, passed through a grading tumbler and returned to the sea, the incidental fishing mortality on the stock is likely to be reduced. This is likely to benefit the stock and have positive effects on biomass and catch rates of legal sized scallops, thus benefiting fishers.

The project has also benefited research and management in other prawn and scallop trawl fisheries. Details of the performance of square mesh codends in the scallop fishery were provided to Dr Mervi Kangas, Department of Fisheries, Western Australia, who was considering trialling the devices in the Shark Bay scallop fishery.

We have also had requests for information on our TED and square mesh codend charter in the scallop fishery from Dr Jeff Gearhart, NOAA Fisheries, USA, who is trialling bycatch reduction devices in a USA east coast scallop trawl fishery. Jeff wrote "*Thanks very much, I read through your reports today and they are excellent. I'll send along our reports when they are complete. Thanks again. Jeff*".

We believe the fishery would benefit by adopting square mesh codends in the scallop and deepwater eastern king prawn sectors, for the abovementioned reasons. Square mesh codends may also be applicable in the black tiger prawn brood stock collection fishery and other sectors, but the project did not assess the device in these sectors. At the time of writing, the number of operators using square mesh codend BRDs was low, although a separate FRDC-funded project (FRDC 2005/054 *A collaborative extension program by the Queensland Department of Primary Industries and Fisheries, Seanet and Ecofish for the development and adoption of square mesh codends in select prawn and scallop trawl fisheries in Queensland*) was making steady progress with adoption rates.

The research charters have also quantified the effects of TEDs and BRDs on the targeted species of prawns, scallops and Moreton Bay bugs (Table 7.4.2), and also on the permitted species such as Balmain bugs (Figure 9.4.2). Quantifying the effects of the devices on target and permitted species catch rates is an important step in producing accurate time series of standardised catch rates and undertaking stock assessments. For example, catch rates of Moreton Bay bugs are likely to have declined by about 21% (Table 7.4.2) due to the introduction of TEDs, and not because of a decline in biomass. Quantifying the impacts of TEDs and BRDs improves the quality of stock assessment advice provided on these species, thus benefiting fishers.

Changes introduced in the Management Plan (*Fisheries (East Coast Trawl) Management Plan 1999*) not only addressed bycatch but also included the provision for fishers to legally retain and market a suite of byproduct species, referred to as the permitted species. These include barking crayfish (*Linuparus trigonus*), Balmain bugs (*Ibacus* spp.), three spot crabs (*Portunus sanguinolentus*), mantis shrimps, (Stomatopoda), cuttlefish (*Sepia* spp.), octopus (*Octopus* spp.), pipehorses (*Solegnathus* spp.) and pinkies (*Nemipterus* spp.). Landings data indicate that collectively these species are valued at $1–2 million annually (Figure 12.1.1) and that they require management attention. The project has made major contributions to a) understanding of the biology of these species, b) improving their management, and c) reducing the risk of overfishing. Through the research presented in Chapters 12 to 18 and by presenting the results to the Trawl Fishery Scientific Advisory Group (TrawlSAG), we identified and recommended minimum legal sizes for barking crayfish (*L. trigonus*), Balmain bugs (*Ibacus* spp.) and three spot crabs (*P. sanguinolentus*). We now have a much clearer understanding of the three species that make up the Balmain bug landings in Queensland, which species are the most valuable and what further research is required. Similarly, the project has provided a clearer understanding of a) the distribution and species composition of nemipterid catches (i.e., pinkies), and b) key population parameter values that can be used to manage them. These are the first reported descriptions of the population dynamics for *N. theodorei* globally. The research, recommendations and management measures that have come from the project will help to maximise the value of these resources and reduce the risk of overfishing.

20 Further development

The research charters showed that bycatch rates in the saucer scallop fishery and the deepwater eastern king prawn fishery could be reduced by a mean of 77% and 29% respectively, by using square mesh codend BRDs with TEDs, with no loss of marketable scallops or prawns. These levels of reduction are much considerably greater than those currently achieved by vessels operating in these sectors. The 77% and 29% reductions equate to several thousands tonnes of bycatch annually when extrapolated upwards to the fleets operating these sectors. We recommend that square mesh codends be made mandatory in these two sectors.

A detailed strategic policy and direction on trawl bycatch in Queensland needs to be developed, which should include future research priorities. While the 40% bycatch reduction review event in the Trawl Management Plan was well intentioned, it is not practically possible to measure with statistical confidence. An alternative policy with clearly stated objectives is required. Importantly, any review of trawl bycatch policy in Queensland should acknowledge that, at present, individual fishers are not legally required to reduce or minimise their bycatch rates, but rather they are only required to install BRDs. Specific questions need to be addressed: a) What are the objectives of bycatch reduction? b) How much bycatch reduction is adequate for (i) individual fishers? and (ii) the fleet? c) Should bycatch monitoring programs be implemented? d) Can change in bycatch species catch rates be detected? and e) If a decline is detected, what action, if any, should be taken?

The project made a significant contribution to understanding the population dynamics of, and providing management advice on, barking crayfish, three spot crabs, mantis shrimp, Balmain bugs, pipehorses and nemipterid fishes, but further research is required to optimise and sustain the value of these stocks. Although some cuttlefish and octopus data were collected during the project, the limited duration for the permitted species research (i.e., project funds and duration were limited to two years only for the permitted species) and lack of specific funding to purchase regular samples and process statoliths for age determination prevented us from providing robust advice on these species. Consideration needs to be given to a) how to attract research funding for these relatively low-value species, and b) fishery-independent monitoring. For some permitted species (i.e., Balmain bugs, nemipterids, pipehorses, three spot crabs, cuttlefish and octopus) fishery-independent monitoring might be achieved by incorporating it into the principal target species' monitoring programs. Barking crays do not appear to be associated with any of the principal target species, and so a separate monitoring program may be required for them. There are problems with a) how the permitted species are differentiated by fishers and therefore recorded in logbooks, and b) incidental catches for many permitted species that are not retained or recorded by fishers. Fishery-independent monitoring would help alleviate some of these problems.

21 Planned outcomes

1. <u>Better understanding of bycatch rates and composition, and quantitative information on the effects of TEDs and BRDs in the Queensland trawl fishery</u>

One of the planned outcomes is a much more informed understanding by commercial and recreational fishers, the Queensland Government, the Great Barrier Reef Marine Park Authority and the public of what the bycatch is comprised of in each of the major Queensland trawl sectors. We have achieved this by: a) measuring bycatch rates from 1619 individual trawls; b)weighing 49.1 t of bycatch on board vessels; c) processing 9.8 t of bycatch to species level in the laboratories; d) documenting the catch rates, mean size and frequency of occurrence for over 1300 bycatch species; e) and importantly, by disseminating this information.

Some of the planned outcomes went beyond what was required of the project. For example, the project:

- not only included documenting the bycatch rates and composition, but we also examined how bycatch assemblages vary with latitude, depth and BRD-type in each of the major sectors;
- went much further than assessing the effects of TEDs and BRDs on mean bycatch rates (i.e., all species pooled). The project went to great lengths to quantify the effects of TEDs and BRDs on the catch rate and mean length of those individual bycatch species that comprise the bulk (i.e., around 90%) of the bycatch weight in each sector; and
- did not limit sampling to either the research charters or the opportunistic measures of bycatch rates, but rather adopted both approaches in order to provide stakeholders with information from both controlled scientific experiments as well as “real world” commercial vessel data.

An important planned outcome from the project is that the fishery managers can use the information to assess how well bycatch reduction management initiatives are progressing in Queensland.

By quantifying the mean catch rates and variances for many bycatch species and undertaking power analyses, managers and decision makers are now in a much better position to design and implement a bycatch monitoring program that is capable of detecting impacts on bycatch species’ populations.

2. Improved understanding of, and advice on, the permitted species

Although no specific planned outcomes were provided for the permitted species research in the original project agreement, the project has made a major contribution to understanding the population dynamics of these species and implementing robust management measures. An important outcome from the project was the introduction of a minimum legal size for three spot crabs, which was a direct result of our yield-per-recruit analysis and advice. Another important outcome was that we identified that the Queensland Balmain bug catches were comprised of three species, all with different distributions and population dynamics, and we have provided advice on minimum legal sizes of each of these species to managers and the Trawl Scientific Advisory Group (TrawlSAG). By providing the first description of the reproductive biology and distribution of barking crayfish *L. trigonus*, the fishery managers are now in a much stronger position to implement management measures for this species. Managers are now in a much more informed position to make decisions about mantis shrimp catches. Based on our findings on catch rates, distribution, sizes and faunal community associations for pipehorses *Solegnathus* spp., which are considered vulnerable and are listed on the International Union for the Conservation of Nature

Red List, the fishery managers are in a much stronger position to make informed decisions about these species.

The project's efforts to inform stakeholders and disseminate information, which contribute directly to the planned outcomes, are reflected in the publications, conferences and presentations that project staff contributed to:

Scientific papers in journals of international standing

1. Haddy, J. A., Roy, D. P., Courtney, A. J., 2003. The fishery and reproductive biology of barking crayfish, *Linuparus trigonus* (Von Siebold, 1824) in the Queensland East Coast Trawl Fishery. *Crustaceana* 76(10):1189-1200.

2. Haddy, J. A, Courtney, A. J., Roy, D. P., 2004. Aspects of the reproductive biology and growth of Balmain bugs (Ibacus spp.) (Scyllaridae). *Journal of Crustacean Biology*. 25(2):263–273

3. Courtney, A. J., Tonks, M. J., Campbell, M., Roy, D. P, Gaddes, S.W., O'Neill, M. F., 2006. Quantifying the effects of bycatch reduction devices in Queensland's (Australia) shallow water eastern king prawn (*Penaeus plebejus*) trawl fishery. *Fisheries Research* 80:136-147.

4. Kyne, P.M., Johnson, J.W., Courtney, A.J., Bennett, M.B., 2005. New biogeographical information on Queensland chondrichthyans. *Memoirs of the Queensland Museum* 50(2): 321-327.

5. Marshall, A.D., Kyne, P.M., Bennett, M.B., (In prep.). Comparative dietary analysis of two sympatric urolophid elasmobranchs from subtropical Australian waters [Planned submission to *Journal of Fish Biology*].

6. Kyne, P.M., Courtney, A.J., Bennett, M.B., (In prep.). Aspects of the reproductive biology and diet of *Dipturus polyommata* (Ogilby, 1910) (Elasmobranchii: Rajidae) from southern Queensland, Australia [Planned submission to *Journal of Fish Biology*].

7. Turner, T.B., Kyne, P.M., Bennett, M.B., 2003. Description of *Paeon asymboli* n. sp. (Copepoda: Sphyriidae), parasitic on *Asymbolus* catsharks, and a new host record for *Paeon australis* Kabata, 1993. *Systematic Parasitology* 56: 235–239.

8. Kyne, P.M., Courtney, A.J., Campbell, M.J., Chilcott, K.E., Gaddes, S.W., Turnbull, C.T., van der Geest, C.C., Bennett, M.B., 2002. An overview of the elasmobranch bycatch of the Queensland East Coast Trawl Fishery (Australia). *NAFO Scientific Research Council Document* 02/97.

9. Johnson, J. W., 2004. Two new species and two new records of Aploactinid fishes (Pisces: Scorpaeniformes) from Australia. Australian Museum 56:179–188.

10. Kyne, P.M., Courtney, A.J., Bennett, M.B., 2006. Additional records of the rock shrimp *Sicyonia australiensis* Hanamura and Wadley, 1998 (Decapoda, Sicyoniidae) from eastern Australia, Western Central Pacific. *Crustaceana* 79(9):1141-1144.

Book contributions

11. Haddy, J.A., Stewart, J,. Graham, K.J., (2007) Fishery and biology of commercially exploited Australian fan lobsters (*Ibacus* spp.) In: Lavalli, K., Spanier, E., (eds.) The Biology and Fisheries of the Slipper lobster. CRC Press. Taylor & Francis Group Publishers, New York.

Conference presentations

12. Peter M. Kyne, David J. Mossop, Ross K. Daley, Rob W. Day, Terence I. Walker and Michael B. Bennett. Comparative reproductive biology of the orange-spotted catshark, *Asymbolus rubiginosus* Last, Gomon & Gledhill, 1999, from eastern Australia. Seventh Indo-Pacific Fish Conference, Taipei, Taiwan, 16–20 May 2005. Oral presentation.

13. Peter M. Kyne, Anthony J. Courtney and Michael B. Bennett. Life history and bycatch of the argus skate *Dipturus polyommata* Ogilby, 1910 in the Queensland East Coast Trawl Fishery, Australia. Conservation and Management of Deepsea Chondrichthyan Fishes, Dunedin, New Zealand, 27–29 November 2003. Poster presentation.

14. Courtney, A.J., Tonks, M. L., Campbell, M. J., Chilcott, K. E., Gaddes, S. W., Roy, D. P., Haddy, J. A., Kyne, P. M., Turnbull, C., van der Geest, C., 2002. Bycatch composition and the effect of bycatch reduction devices in the Queensland trawl fishery. In "Proceedings of the Australian Society for Fish Biology Annual Conference" August 2002, Cairns, Queensland.

15. Campbell, M., Chilcott, K., Courtney, A. J. Gaddes, S., Kyne, P., Roy, D., Tonks, M., Turnbull, C., van der Geest, C., 2003. Reducing bycatch in Queensland's trawl fishery – experimental charters using nets with square mesh codends show promising results. In: "Proceedings of the Australian Society for Fish Biology Annual Conference", 29 June – 4 July 2003, Wellington, New Zealand.

16. Courtney, A.J., Campbell, M., Tonks, M., Roy, D., Chilcott, K., Gaddes, S. W., O'Neill, M., van der Geest, C., Turnbull, C., Rose, C., Kistle, S., Kyne, P., 2004. Quantifying bycatch and the effects of BRDs in Queensland's Trawl Fishery: observations from fishing vessels and research charters. In: "Proceedings of the National Prawn Industry Conference", 28–30 November 2004, Cairns, Queensland.

17. Peter M. Kyne, Anthony J. Courtney, Matthew J. Campbell, Keith E. Chilcott, Shane W. Gaddes, Clive T. Turnbull, Claire C. van der Geest, Michael B. Bennett. An overview of the elasmobranch bycatch of the Queensland East Coast Trawl Fishery (Australia). Symposium on Elasmobranch Fisheries:

Managing for Sustainable Use and Biodiversity Conservation, Santiago de Compostela, Spain, 11–13 September 2002.

18. Courtney, A. J., Campbell, M. J., Tonks, M. L., Roy, D. P., Chilcott, K. E., Gaddes, S. W., O'Neill, M. F., Kyne, P. M., 2005. Round scallops and square meshes: promising field trials with bycatch reduction devices (BRDs) reduce both bycatch and undersized scallop catches. 15th International Pectinid Workshop, Mooloolaba, Queensland, Australia, 21–26 April 2005.

19. Haddy, J. A., Aspects of the reproductive biology and growth of Balmain bugs (*Ibacus* spp.). Australian Marine Sciences Association (AMSA) Annual Conference, Brisbane, July 2003.

20. Courtney, A. J., Campbell, M. J., Tonks, M. L., Roy, D. P., Chilcott, K. E., Gaddes, S. W., O'Neill, M. F., van der Geest, C., Turnbull, C., Rose., C., Kistle, S., Kyne, P. M., Ballam, D. Research and extension on trawl bycatch reduction in Queensland. Presented at "Investigating options to improve bycatch reduction in tropical prawn fisheries: a workshop for fishers" Cairns Yacht Squadron, Cairns, Queensland, 21–22 November 2006.

Non-refereed articles

21. Kyne, P. (2002). Elasmobranch bycatch in Queensland's East Coast Trawl Fishery. *Queensland Regional Ripples* 8(4): 4.

22. Brown, I.W., Courtney, A.J., Campbell, M.J., Chilcott, K.E. and McLennan, M. (2003). *Winter (diver) whiting trawl bycatch in southern Hervey Bay*. AFFS Report to the Queensland Fisheries Service.

23. Courtney, A. J. (2002). Research results on the effects of bycatch reduction devices in the eastern king prawn fishery. *Queensland Fisherman* 20(6):20-23.

24. Courtney, A. J. and M. Campbell (2003). Square mesh BRDs show good results. *Queensland Fisherman* 21(1):32-35.

25. Campbell, M. and Courtney, A. J. (2003). Square mesh BRDs show good results. *Professional fisherman* 25(4):12-16.

26. Campbell, M. and Courtney, A. J. (2003). Reducing bycatch in the Queensland scallop fishery. *Professional fisherman* 25(8):18-19.

27. Courtney, A. J. and M. Campbell (2003). DPI studies bycatch in scallop fishery. *Queensland Fisherman* 21(9):39-43.

28. Courtney, A. J., Tonks, M. L., Roy, D. P., Haddy, J. A., Jebreen, E. J. and Campbell, M. J. (2003). *Exploring associations between pipehorse (Solegnathus cf. hardwickii) abundance and bycatch faunal communities in the Queensland trawl fishery*. AFFS Report to the Queensland Fisheries Service.

Presentations

29. Peter M. Kyne. Catching sharks by accident. Elasmobranch bycatch of the Queensland East Coast Trawl Fishery. Natural Sciences Postgraduate Day 2002 (organised by The Royal Society of Queensland and The Queensland Museum), Brisbane, Australia, 26 October 2002. Oral presentation.

30. M. J. Campbell. Results of Research – The effects of TEDs and BRDs in the Queensland trawl fishery. QFS Workshops at Mooloolaba, Southport, Scarborough, Bundaberg, Gladstone, Mackay, Bowen, Townsville and Cairns, 22 April – 2 May 2004.

31. M. J. Campbell. Bycatch reduction using square mesh codends in the Queensland scallop fishery. Southern Fisheries Centre Seminar Series, Deception Bay, 20 June 2003.

32. M. J. Campbell. TEDs in Queensland: a summary of a TED and BRD extension project. QFS TED workshop, Brisbane, 21 May 2003.

33. M. J. Campbell. Research results from a charter in the shallow water eastern king prawn fishery. QFS Bycatch workshop, Brisbane, 23 May 2002.

34. J. A. Haddy. Biology and population dynamics of byproduct in the Queensland East Coast Trawl Fishery (QECTF). Presentation to the Queensland Trawl Fishery Scientific Advisory Group (TrawlSAG). February 2003.

22 Conclusion

Objective 1
Describe the bycatch species composition and catch rates under standard trawl net conditions (non-TED and non-BRD) in Queensland's major trawl sectors (eastern king prawn, scallop and tiger/endeavour prawn sectors).
Objective 2
Describe the bycatch species composition and catch rates when nets have TEDs and BRDs installed in Queensland's major trawl sectors (eastern king prawn, scallop and tiger/endeavour prawn sectors).
Objective 3
Test and quantify the impact of different combinations of TEDs and BRDs on bycatch and target species against standard nets under controlled experimental conditions using chartered commercial trawlers in the eastern king prawn, scallop and tiger/endeavour prawn sectors.

The project obtained 1619 measurements of trawl bycatch rates and sub-samples of bycatch from dedicated research charters and from opportunistically sampling the commercial fishing vessels throughout the major Queensland trawl fishery sectors. From the opportunistic measures we quantified the effects of the bycatch reduction devices (both TEDs and BRDs) that fishers are using on prawn, scallop and bycatch

catch rates. The research charters provided information on potential bycatch reduction that could be achieved with select devices. In general, the research charters demonstrated that bycatch can be reduced by significantly greater amounts than what is occurring in the commercial fishery.

No significant reduction was detected in the mean total bycatch rate in the combined prawn sectors due to TEDs and BRDs (Table 10.4.3). However, a significant reduction of 25% was detected when large fauna were omitted from the analyses (i.e., bycatch excluding monsters, Table 10.4.3). The reductions achieved in the research charters conducted in the prawn sectors were substantially greater than this. For example, the deepwater eastern king prawn fishery charter demonstrated that the mean total bycatch rate could be reduced by 29% (Table 9.4.1) compared to a standard net, by using a TED and square mesh codend, with no loss of prawns. Collectively, the results suggest that in the prawn trawl sectors, fishers could do more to increase their bycatch reduction. In the scallop fishery, fishers have decreased their mean total bycatch rate substantially (68% reduction in mean total bycatch rates, Table 10.4.7), mainly due to the TEDs excluding large sponges which comprise much of the bycatch weight in the sector.

With respect to describing the bycatch and the effects of bycatch reduction devices on bycatch species, project staff weighed 49.1 t of bycatch on board vessels and processed 9.8 t of bycatch to species level in the QDPI&F Northern Fisheries Centre and Southern Fisheries Centre laboratories. The project quantified catch rates, mean length and frequency of occurrence of about 1320 bycatch species in the major sectors (see Appendices 1–5). The effects of TEDs and BRDs on the catch rate and mean length of the dominant species in each sector were also analysed. The project demonstrated that some species could be almost eliminated from the bycatch in certain sectors (Table 7.4.3).

In addition to considering the effects of TEDs and BRDs on individual bycatch species, we also examined how the bycatch assemblages varied with depth and latitude and codend treatment type. In general, the bycatch assemblages appeared unlikely to change significantly as a result of TEDs and BRDs, with the exception of the scallop fishery where a marked difference was apparent, mainly due to the square mesh codend (Figure 7.5.1).

Objective 4
Review the known biology and distribution of all recently approved "permitted fish" species associated with the trawl fishery.
Objective 5
Quantify key population parameter estimates, including growth rates, size at maturity, distribution and landings, for all recently approved "permitted fish" species.

When the Trawl Fishery Management Plan [*Fisheries (East Coast Trawl) Management Plan 1999*] was altered and fishers were permitted to retain a large number of incidentally captured species [i.e., barking crayfish (*L. trigonus*), Balmain bugs (*Ibacus* spp.), three spot crabs (*P. sanguinolentus*), mantis shrimps, (Stomatopoda), cuttlefish (*Sepia* spp.), octopus (*Octopus* spp.), pipehorses (*Solegnathus* spp.) and pinkies (*Nemipterus* spp.)] it was apparent that significantly more research was required to manage these species on a sustainable basis. While it was beyond the scope of the project to quantify the key population parameter estimates for all permitted species (i.e., there are over 50 species that make up the permitted species), the research presented in Chapters 12–18 represents a significant contribution to this cause. Minimum legal sizes for barking crayfish, Balmain bugs and three spot crabs, based on quantitative biological information from the project, have been recommended. Although the range of management options for pipehorses is limited (i.e., minimum legal sizes seem inappropriate, closures and gear restrictions would impact on target species), managers are now in a much more informed position to make decisions about these species, based on the information provided on their distribution, catch rates, depth of capture, size class frequencies and the faunal communities that they are associated with. The project provided the first detailed information on the distribution, length-frequencies, growth rates, size at maturity and seasonal variation in reproduction for pinkies *N. theodorei* and *N. aurifilum,* and represents the first records of the population dynamics reported for *N. theodorei.*

Objective 6
Apply power analysis to determine how many trawl samples are needed to detect various levels of change in individual bycatch species catch rates.

This objective was achieved by using the mean catch rates and variance estimates of several bycatch species from the north Queensland tiger/endeavour prawn charter (section 6.4.4) and the deepwater eastern king prawn charter (section 9.4.5). Power analyses were considered for species with catch rate distributions that conform to gamma or binomial distributions. A monitoring program with two levels of trawl sampling effort were considered, one based on 30 trawl samples and one based on 300. We also considered two levels of change or “bycatch reference points” that managers might consider: a 40% decline in catch rate, and an 80% decline in catch rate. The power to detect change in bycatch species catch rates increases with a) decreasing variance, b) increasing probability of capture, and c) increasing size of the change. The results can be used to develop monitoring programs and detect changes with confidence. Perhaps a more challenging problem pertains to what actions should be taken if or when a change is detected for one of more bycatch species.

Objective 7
Provide advice on the guidelines and definitions of BRDs and TEDs so that the Boating and Fisheries Patrol can confidently enforce regulations.

Project staff actively contributed to improving the guidelines and definitions of BRDs and TEDs throughout the project, and continue to do so. Two project staff, Tony Courtney and Matthew Campbell, are members of the trawl fishery Technical Working Group, which includes Boating and Fishing Patrol Officers and was formed specifically to address TED and BRD technical issues. Project staff provided advice by a) participating in the Technical Working Group, b) running courses on the design and definitions of TEDs and BRDs with fishers and Patrol Officers, c) working cooperatively with the Patrol on TED and BRD prosecutions as expert witnesses, d) promoting improvements to BRD definitions and specifications, e) developing rigorous procedures and methodologies to evaluate recognised BRDs (i.e., already listed in the Plan) and new designs as they are put forward, and f) presenting results from the project’s research charters that tested TEDs and BRDs. Examples of project staff involvement with the Patrol on matters pertaining to TEDs and BRDs are provided in the following table.

Examples of project staff improving TED and BRD definitions, specifications and interaction with the Queensland Boating and Fisheries Patrol.

Date	**Event**	**Purpose**
July 2001	Technical Working Group meeting, Brisbane	To discuss the definitions and specifications of BRDs. Project staff successfully argued that the definitions required improvement and obtained a commitment from the Group, industry and government to improve the technical specifications of BRDs, making them more effective.
September 2001	Reviewed the definitions of TEDs and BRDs	Provide further advice to managers and Patrol to improve BRDs
September 2001	Legal infringement of TED and BRD	Provided advice as expert witness
October 2001	Patrol sought project staff advice	Provide advice on TED designs for beam trawl fishery
November 2001	Patrol sought advice from project staff	Certain fishers were arguing to increase the TED bar spacings from 12 cm to 15 cm. This would have resulted in a higher proportion of small/young turtles passing through the TED and into the codends. Project staff successfully argued against this.
February 2002	Patrol sought advice on disseminating BRD guidelines	Project staff undertook detailed drawings of BRDs and provided them to Patrol
August 2002	Technical Working Group meeting, Cairns	To present research charter results on the performance of TEDs and BRDs. Successfully argued to amend several BRD definitions, including limiting the distance of several BRDs to 100 meshes of the drawstring.
May 2002	QFS Bycatch workshop, Brisbane	To communicate research results from the shallow water eastern king prawn charter that tested a TED and radial escape section BRD
May 2003	QFS TED workshop, Brisbane	Presentation of the results on TEDs in Queensland and summary of TED and BRD extension project
April to May 2004	QFS workshops at Mooloolaba, Southport, Scarborough, Bundaberg, Gladstone, Mackay, Bowen, Townsville and Cairns	Present project research results on the effects of TEDs and BRDs on bycatch rates
March 2003, May 2004, June 2005 and February 2006	Boating and Fisheries Patrol educational course, Southern Fisheries Centre, Deception Bay	Demonstrate several TED and BRD designs to new Patrol recruits, so they could become familiar with policing the devices

23 Acknowledgements

The project was funded by the Australian Fisheries Research and Development Corporation (Project number 2000/170) and we thank FRDC for their support. We are grateful for the taxonomic advice provided by Queensland Museum staff Jeff

Johnson, Steve Cook, Peter Davie and Darryl Potter. Thanks to Mark McGrouther, Kerryn Parkinson and John Pogonoski at the Australian Museum and to Leonard J.V. Compagno and Tracey Turner.

We also thank Peter Gaddes and Phil Pearson for their seamanship aboard the *Elizabeth G* during the eastern king prawn charters and Glen Chisholm from the QDPI&F Northern Fisheries Centre who competently skippered the QDPI&F *RV Gwendoline May* during the tiger/endeavour prawn charter. Thanks also to the Flaherty family, Colin, Darren and Wayne, for making their vessel *Southern Intruder* available for the scallop charter, for helping construct the nets used in the charter, for the underwater filming of the square mesh codends and for skippering the vessel. We would like to thank Reg Saunders for his support while skippering the commercial trawler *Lewis Venture* during the Hervey Bay whiting bycatch charter. Kevin Wicks provided advice about the gear used by fishers and most of the nets used for the charters. Jason Gerharty from ATS Nets and Ropes organised the importation of square mesh bundles. We thank Matt Broadhurst from the New South Wales Department of Primary Industries for providing advice on square mesh codends. We are indebted to the many Queensland commercial trawler fishers and processors who provided samples of the permitted species, generously donated samples or allowed project staff on board their vessels to obtain opportunistic measures of bycatch rates and bycatch samples. Special thanks to Peter Duncan, Tony Sterling, Geoff Whitehouse, Geoff Tilton, Peter Seib, R. Damon, Rob Hobson and Richard Pillans for providing samples of barking crays, Balmain bugs, nemipterids and elasmobranchs, and information on their distributions.

We would like to thank the project steering committee members: Ilona Stobutzki and David Brewer (CSIRO, Cleveland), Robin Hansen (trawl fisher, State Trawl Representative), Barry Ehrke (trawl fisher, North), Brigid Kerrigan (QDPI&F QFS Trawl Fishery Manager), Mark Lightowler (QDPI&F QFS Fishery Resource Officer, Trawl), Duncan Souter (Queensland Seafood Industry Association) and David Mayer (QDPI&F Biometry). John Olsen (trawl fisher, QSIA President) attended some steering committee meetings as an observer.

Wayne Sumpton, Jenny Ovenden, Mike Allen, John Stewart and Lauren Keim provided helpful discussion and critically reviewed manuscript drafts. We also thank the QDPI&F Southern Fisheries Centre staff of Tony White, Keely Moran, Kelly Breddin, Melissa Whitford and Bob Cooper for administrative and financial assistance associated with the project.

24 Intellectual property

No intellectual property has arisen from the work.

25 Staff

Dr Tony Courtney, Senior Fisheries Biologist (Principal Investigator)
Mr Clive Turnbull, Senior Fisheries Biologist (Co-investigator)
Dr James Haddy, Fisheries Biologist
Mr Matthew Campbell, Fisheries technician
Mr Mark Tonks, Fisheries technician

Mr Darren Roy, Fisheries technician
Ms Claire van der Geest, Fisheries technician
Ms Sarah Kistle, Fisheries technician
Ms Cassie Rose, Fisheries Biologist
Mr Keith Chilcott, Fisheries technician
Mr Shane Gaddes, Fisheries technician
Mr Michael O’Neill, Senior Fisheries Biologist

Mr Peter Kyne, Ph.D. candidate from the University of Queensland, was heavily involved in the project but was not a staff member.

Appendix 1. List of 406 taxa in the bycatch of the Queensland shallow water (< 91 m) eastern king prawn trawl fishery based on bycatch sub-samples from 204 individual net trawls from the research charter and opportunistically sampling the commercial fleet between April 2000 and April 2002. Mean catch rates are in grams and numbers per hectare, mean lengths (mm) are fork length or standard length for fish, carapace length for crustaceans, disc width or length for elasmobranchs, total length for echinoderms, and shell length for molluscs. Includes small or undersize principal target and permitted species. Frequency is the percentage occurrence in 204 net trawls. Standard error in brackets.

Species	Mean catch rate g ha^{-1}	Mean catch rate n ha^{-1}	Mean length mm	Frequency of capture (%)
Abalistes stellaris	0.023 (0.022)	0.002 (0.002)	55 (0)	0.5
Acalyptophis peronii	0.118 (0.113)	0.009 (0.009)		0.5
Acanthocepola limbata	0.118 (0.112)	0.001 (0.001)	500 (0)	0.5
Actinopyga miliaris	0.099 (0.095)	0.004 (0.004)	105 (0)	0.5
Aesopia sp.	0.023 (0.022)	0.001 (0.001)	105 (0)	0.5
Albunea occultus	0.046 (0.044)	0.006 (0.006)	18 (0)	0.5
Alima sp.	0.045 (0.036)	0.004 (0.003)	22 (2)	1
Ambiserrula jugosa	0.036 (0.034)	0.001 (0.001)	155 (0)	0.5
Amusium balloti	77.741 (28.288)	3.779 (1.037)	56.71 (0.81)	34.3
Anacanthus barbatus	0.041 (0.039)	0.003 (0.003)	170 (0)	0.5
Anchisomus multistriatus	0.422 (0.402)	0.006 (0.006)	100 (0)	0.5
Ancillista velesiana	0.487 (0.222)	0.01 (0.005)	66.4 (5.87)	2.5
Anoplocapros inermis	61.982 (11.821)	0.172 (0.031)	179.75 (2.81)	15.7
Antennarius hispidus	0.002 (0.002)	0.001 (0.001)	40 (10)	0.5
Antennarius striatus	1.447 (0.391)	0.082 (0.019)	53.75 (2.17)	12.7
Anthenea sp.	0.241 (0.164)	0.006 (0.004)	110 (25)	1
Antigonia rhomboidea	0.26 (0.089)	0.046 (0.015)	36.5 (1.37)	8.8
Apistus carinatus	15.365 (4.864)	0.526 (0.19)	92.91 (1.89)	11.8
Aploactis aspera	0.151 (0.06)	0.039 (0.015)	50.31 (2.26)	4.9
Aplysia dactylomela	0.132 (0.126)	0.008 (0.008)	90 (0)	0.5
Apogon brevicaudata	0.345 (0.328)	0.017 (0.016)	76.67 (8.82)	0.5
Apogon capricornis	1.206 (0.402)	0.142 (0.049)	65.68 (1.24)	5.4
Apogon ellioti	0.416 (0.215)	0.028 (0.012)	72.5 (6.68)	2.9
Apogon fasciatus	2.136 (0.643)	0.172 (0.051)	69.64 (1.26)	7.4
Apogon nigripinis	5.184 (1.025)	0.449 (0.083)	56.89 (1.22)	18.1
Apogon poecilopterus	0.397 (0.225)	0.018 (0.01)	80 (5.77)	1.5
Apogon semilineatus	2.837 (0.875)	0.282 (0.089)	67.46 (1.49)	10.3
Apogon septemstriatus	0.289 (0.113)	0.055 (0.019)	54.55 (2.47)	4.4
Apogon sp.	0.002 (0.002)	0.002 (0.002)	35 (0)	0.5
Aptychotrema rostrata	93.27 (10.735)	0.507 (0.094)	412.83 (9.17)	45.1
Arcania elongate	0.004 (0.003)	0.001 (0.001)	17 (0)	0.5
Arnoglossus elongatus	0.073 (0.069)	0.006 (0.006)	115 (10)	0.5
Arnoglossus fisoni	80.871 (13.553)	6.25 (1.057)	107.59 (0.53)	16.7
Arnoglossus sp.	0.03 (0.028)	0.006 (0.006)	75 (0)	0.5
Arnoglossus waitei	0.346 (0.112)	0.065 (0.018)	73.37 (1.95)	9.3
Arothron stellatus	0.06 (0.044)	0.011 (0.008)	32.5 (2.5)	1
Arotrolepis filicauda	0.316 (0.173)	0.035 (0.021)	59.17 (6.25)	1.5
Aseraggodes macleayanus	4.107 (1.712)	0.071 (0.029)	145.83 (5.74)	4.4
Aseraggodes melanospilus	0.067 (0.064)	0.004 (0.004)	100 (0)	0.5
Aseraggodes melanostictus	0.328 (0.191)	0.017 (0.009)	110 (10)	1.5
Ashtoret lunaris	0.787 (0.29)	0.12 (0.04)	33.28 (1.55)	4.9
Astele bularra	0.124 (0.118)	0.019 (0.019)	26.67 (1.67)	0.5
Astele speciosum	0.031 (0.03)	0.005 (0.005)	25 (0)	0.5
Asterorhombus intermedius	0.054 (0.051)	0.005 (0.004)	100 (0)	0.5

Species	**Mean catch rate g ha^{-1}**	**Mean catch rate n ha^{-1}**	**Mean length mm**	**Frequency of capture (%)**
Astropecten sp.	2.323 (0.526)	0.226 (0.038)	74.16 (3.03)	22.1
Asymbolus analis	1.598 (0.818)	0.004 (0.002)	462.5 (4.79)	2
Asymbolus rubiginosus	0.809 (0.77)	0.003 (0.003)	456.5 (1.5)	0.5
Athrinomorus ogilbyi	0.027 (0.026)	0.002 (0.002)	90 (0)	0.5
Aulopus curtirostris	0.255 (0.119)	0.034 (0.015)	74.48 (1.84)	3.4
Aulotrachichthys sp.	0.138 (0.07)	0.034 (0.015)	46.7 (0.85)	5.9
Basket star	0.048 (0.023)	0.004 (0.002)	36 (6)	2.5
Batrachomoeus dubius	3.427 (1.77)	0.117 (0.058)	89.17 (5.03)	2.5
Bellosquilla laevis	7.594 (1.952)	0.52 (0.13)	23.44 (0.34)	10.8
Bolma aureola	0.209 (0.193)	0.007 (0.005)	31.33 (8.51)	1.5
Brachaluteres taylori	0.621 (0.283)	0.08 (0.035)	40 (1.54)	4.9
Brittle star	0.134 (0.055)	0.039 (0.015)	113.13 (19.84)	4.4
Calappa lophos	4.198 (1.842)	0.041 (0.02)	86.78 (5.85)	3.9
Calappa philargius	6.428 (2.097)	0.089 (0.028)	73 (5.27)	4.9
Calliactus sp.	0.988 (0.325)	0.055 (0.018)	38.29 (2.83)	7.8
Callionymus calcaratus	283.475 (42.293)	11.479 (1.9)	122.73 (0.45)	49.5
Callionymus grossi	0.12 (0.084)	0.004 (0.003)	147.5 (7.5)	1
Callionymus japonicus	26.987 (5.732)	1.502 (0.293)	116.42 (1.17)	35.3
Callionymus limiceps	276.111 (38.847)	13.278 (2.118)	119.64 (0.61)	46.1
Callionymus margaretae	0.044 (0.042)	0.001 (0.001)	160 (0)	0.5
Callionymus moretonensis	0.921 (0.256)	0.083 (0.019)	91.75 (2.63)	14.7
Cantheschenia longipinnis	0.275 (0.261)	0.005 (0.004)	115 (0)	0.5
Canthigaster callisterna	0.161 (0.084)	0.011 (0.005)	55.71 (7.11)	3.4
Carangoides equula	1.172 (0.259)	0.095 (0.019)	68.59 (1.92)	14.7
Carangoides hedlandensis	0.13 (0.091)	0.013 (0.009)	60 (5)	1
Carangoides humerosus	0.417 (0.397)	0.006 (0.006)	130 (0)	0.5
Carangoides sp.	0.031 (0.026)	0.005 (0.004)	60 (5)	1
Carangoides talamparoides	0.313 (0.298)	0.012 (0.012)	82.5 (22.5)	0.5
Carid sp.	0.001 (0.001)	< 0.001	14 (0)	0.5
Centroberyx affinis	0.001 (0.001)	< 0.001	30 (0)	0.5
Centropogon australis	2.841 (0.962)	0.216 (0.075)	66.43 (1.37)	6.4
Chaetodermis penicilligrus	0.195 (0.146)	0.004 (0.003)	97.5 (32.5)	1
Chaetodon citrinellus	0.018 (0.017)	0.003 (0.003)	50 (0)	0.5
Chaetodon guentheri	0.14 (0.088)	0.006 (0.003)	77.5 (5.95)	2
Champsodon nudivittis	0.009 (0.007)	0.002 (0.001)	65 (15)	1
Charybdis bimaculata	1.205 (0.241)	0.101 (0.02)	37.36 (0.28)	13.7
Charybdis feriatus	7.343 (4.887)	0.051 (0.016)	74.11 (12.89)	4.4
Charybdis jaubertensis	0.037 (0.036)	0.005 (0.005)	25 (0)	0.5
Charybdis miles	0.145 (0.1)	0.002 (0.001)	77.5 (0.5)	1
Charybdis natator	6.992 (2.437)	0.121 (0.035)	57.05 (4.32)	7.4
Charybdis sp.	0.11 (0.105)	0.003 (0.003)	50 (0)	0.5
Charybdis truncata	0.34 (0.188)	0.035 (0.02)	33 (3.45)	2
Chelidonichthys kumu	4.75 (1.788)	0.042 (0.015)	173.5 (2.88)	7.4
Chloeia sp.	0.023 (0.015)	0.008 (0.006)	43.75 (6.57)	1.5
Choerodon cephalotes	0.326 (0.311)	0.004 (0.003)	130 (0)	0.5
Choerodon frenatus	2.643 (0.594)	0.147 (0.033)	81.16 (1.75)	17.2
Choerodon venustus	0.058 (0.056)	0.003 (0.003)	81.67 (13.02)	0.5
Chromis abyssicola	0.102 (0.056)	0.004 (0.002)	79 (3.32)	2
Cleidopus gloriamaris	3.898 (1.413)	0.028 (0.01)	123.75 (7.12)	3.9
Conger wilsoni	0.296 (0.229)	0.002 (0.001)	487.5 (12.5)	1
Crossorhombus azureus	15.087 (4.809)	0.938 (0.292)	99.37 (1.2)	18.6
Cubiceps whiteleggii	0.04 (0.027)	0.011 (0.008)	47.5 (2.5)	1
Cymbiolista hunteri	0.451 (0.322)	0.004 (0.003)	120 (5)	1
Cynoglossus sp.	15.07 (2.441)	0.511 (0.076)	139.77 (1.82)	33.3

Species	**Mean catch rate g ha^{-1}**	**Mean catch rate n ha^{-1}**	**Mean length mm**	**Frequency of capture (%)**
Cypraea subviridis	0.018 (0.017)	0.004 (0.003)	30 (0)	0.5
Cypselurus sp.	0.105 (0.071)	0.007 (0.006)	107.5 (37.5)	1
Dactyloptena macracantha	0.045 (0.043)	0.001 (0.001)	110 (0)	0.5
Dactyloptena orientalis	0.121 (0.115)	0.005 (0.004)	100 (0)	0.5
Dactyloptena papilio	31.992 (7.785)	1.372 (0.333)	87.06 (0.91)	33.8
Dardanus arrosor	0.552 (0.263)	0.016 (0.007)	28.14 (3.52)	4.9
Dardanus callichela	0.42 (0.378)	0.015 (0.013)	29.5 (0.5)	1
Dardanus crassimanus	0.017 (0.016)	0.002 (0.002)	21 (0)	0.5
Dardanus gemmatus	0.044 (0.042)	0.01 (0.009)	16.5 (1.5)	0.5
Dardanus imbricatus	0.296 (0.203)	0.017 (0.009)	22.33 (3.53)	1.5
Dardanus lagopodes	0.275 (0.253)	0.008 (0.006)	23 (3.16)	1
Dardanus pedunculatus	0.031 (0.029)	0.004 (0.003)	22 (0)	0.5
Dardanus sp.	0.001 (0.001)	0.001 (0.001)	13 (0)	0.5
Dasyatis kuhlii	11.778 (4.259)	0.018 (0.006)	262.92 (19.5)	4.9
Decapterus macrosoma	0.45 (0.428)	0.004 (0.004)	225 (0)	0.5
Decapterus russellii	1.089 (0.651)	0.024 (0.014)	98.75 (15.17)	2
Dendrochirus brachypterus	0.26 (0.115)	0.023 (0.009)	59.29 (6.76)	3.4
Dendrochirus zebra	0.879 (0.831)	0.013 (0.011)	91.25 (24.01)	1.5
Dendrodoris tuberculosa	1.586 (0.422)	0.102 (0.033)	56.61 (2.82)	9.3
Dentex spariformis	0.416 (0.233)	0.036 (0.016)	65.56 (1.8)	4.4
Diagramma pictum	1.022 (0.511)	0.047 (0.019)	79.38 (5.21)	2.9
Diodon holocanthus	6.668 (5.367)	0.036 (0.027)	129.44 (6.74)	1
Dipturus polyommata	0.021 (0.02)	0.001 (0.001)	110 (0)	0.5
Distorsio reticulata	0.006 (0.006)	0.001 (0.001)	34 (0)	0.5
Dorippe quadridens	0.084 (0.08)	0.004 (0.004)	35 (0)	0.5
Eduarctus martensii	0.044 (0.03)	0.012 (0.009)	16.5 (0.5)	1
Eklonia radiata	25.56 (4.339)		60 (0)	34.3
Emmelichthys strusakeri	0.005 (0.005)	0.001 (0.001)		0.5
Engraulis australis	0.083 (0.047)	0.014 (0.009)	90 (8.22)	2
Engyprosopon grandisquama	119.374 (15.849)	11.27 (1.441)	89.95 (0.39)	54.4
Engyprosopon macroptera	14.853 (3.122)	1.147 (0.201)	97.82 (1.04)	29.4
Engyprosopon sp.	22.247 (8.428)	1.286 (0.51)	115.74 (1.18)	10.8
Entomonyx depressus	0.007 (0.004)	0.003 (0.002)	25.75 (3.25)	1.5
Ephippias endeavouri	0.131 (0.125)	0.001 (0.001)	57 (0)	0.5
Epinephelus sp.	0.015 (0.015)	< 0.001	115 (0)	0.5
Eplumula australiensis	0.021 (0.009)	0.091 (0.038)	5.53 (0.16)	5.4
Erosa erosa	2.162 (0.67)	0.108 (0.027)	52.12 (3.7)	10.3
Etrumeus teres	0.358 (0.341)	0.006 (0.006)	160 (0)	0.5
Eubalichthys mosaicus	0.007 (0.007)	0.002 (0.001)	50 (0)	0.5
Eumedonus vicinus	0.02 (0.008)	0.032 (0.013)	11 (0.53)	3.4
Euprymna sp. *B*	0.066 (0.02)	0.023 (0.007)	17.83 (0.75)	6.4
Euprymna sp. *C*	0.025 (0.009)	0.017 (0.006)	13.16 (0.57)	3.9
Euprymna tasmanica	1.601 (0.324)	0.229 (0.051)	22 (0.48)	19.6
Euristhmus nudiceps	4.057 (1.969)	0.068 (0.027)	250 (19.06)	4.4
Eurypegasus draconis	0.008 (0.008)	0.003 (0.003)	50 (0)	0.5
Ficus subintermedia	0.406 (0.226)	0.021 (0.012)	63.33 (3.33)	1.5
Fistularia petimba	0.033 (0.022)	0.001 (0.001)	415 (70)	1
Foetorepus calauropomus	15.479 (4.015)	0.561 (0.143)	105.4 (1.75)	19.1
Fungia sp.	0.054 (0.051)	0.003 (0.003)	55 (0)	0.5
Galearctus timidus	0.03 (0.014)	0.005 (0.002)	19.14 (1.37)	2.5
Gerres subfasciatus	4.072 (2.011)	0.136 (0.068)	100 (2.94)	4.9
Glaucosoma scapulare	13.873 (3.96)	0.876 (0.196)	62.25 (0.98)	23
Gnathophis grahamii	31.552 (6.267)	0.597 (0.117)	286.2 (3.36)	27
Gonorynchus greyi	4.86 (1.172)	0.071 (0.016)	207.5 (9.13)	10.8

Species	**Mean catch rate g ha^{-1}**	**Mean catch rate n ha^{-1}**	**Mean length mm**	**Frequency of capture (%)**
Grammatobothus polyophthalmus	2.325 (0.581)	0.138 (0.03)	111.79 (4.98)	13.2
Gymnocranius audleyi	0.292 (0.232)	0.028 (0.023)	62.14 (1.01)	1
Hemigaleus australiensis	1.784 (1.699)	0.006 (0.006)	440 (0)	0.5
Heterodontus galeatus	12.616 (8.895)	0.006 (0.003)	541.75 (108.36)	2
Heteroscyllium colcloughi	6.916 (4.943)	0.003 (0.002)	717.5 (52.5)	1
Hippocampus queenslandicus	0.086 (0.057)	0.014 (0.007)	105 (10.21)	2
Holothuria ocellata	48.646 (12.396)	0.258 (0.066)	203.77 (4.88)	14.2
Holothurian sp.	1.573 (1.445)	0.025 (0.017)	68 (12.1)	2.5
Holothurian sp. *5*	0.005 (0.005)	0.003 (0.003)	40 (10)	0.5
Holothurian sp. *Z*	1.696 (0.847)	0.198 (0.09)	39.77 (0.97)	6.9
Homola orientalis	0.002 (0.002)	0.001 (0.001)	14 (0)	0.5
Hyastenus campbelli	0.01 (0.008)	0.002 (0.002)	20.5 (1.5)	1
Hyastenus diacanthus	0.03 (0.02)	0.005 (0.003)	21.67 (3.28)	1.5
Hyperlophus vittatus	0.064 (0.061)	0.011 (0.01)	77.5 (2.5)	0.5
Hypnos monopterygius	18.247 (6.402)	0.013 (0.004)	311.36 (25.73)	5.4
Ibacus brucei	0.009 (0.007)	0.002 (0.001)	22.5 (2.5)	1
Ibacus chacei	4.226 (0.753)	0.253 (0.046)	27.64 (0.62)	19.6
Ichthyscopus sannio	1.657 (0.938)	0.031 (0.014)	90 (9.13)	2.9
Inegocia japonica	177.984 (21.797)	6.671 (0.84)	118.55 (0.8)	54.9
Inimicus caledonicus	0.56 (0.363)	0.012 (0.007)	108.33 (6.01)	1.5
Jonas leuteanus	0.017 (0.01)	0.002 (0.001)	34 (2.89)	1.5
Kanekonia queenslandica	0.012 (0.011)	0.005 (0.005)	35 (0)	0.5
Kelp	107.904 (33.436)			7.4
Lactoria diaphana	0.026 (0.025)	0.004 (0.003)	35 (0)	0.5
Laevicardium attenuatum	0.061 (0.058)	0.005 (0.005)	39 (0)	0.5
Lagocephalus sceleratus	0.013 (0.012)	0.007 (0.006)	40 (0)	0.5
Lagocephalus spadiceus	1.37 (1.015)	0.006 (0.003)	162.5 (10.63)	2.5
Leiognathus moretoniensis	0.275 (0.109)	0.109 (0.039)	43.83 (1.31)	6.9
Lepidoperca caesiopercula	2.857 (1.234)	0.092 (0.039)	92.94 (1.8)	8.8
Lepidotrigla argus	1420.314 (106.719)	81.432 (6.244)	86.82 (0.3)	76
Lepidotrigla callodactyla	0.112 (0.107)	0.005 (0.005)	97.5 (12.5)	0.5
Lepidotrigla cf japonica	1.095 (0.475)	0.046 (0.018)	92.14 (5.34)	3.9
Lepidotrigla grandis	1.532 (1.011)	0.058 (0.041)	101.18 (5.47)	1.5
Lepidotrigla papilio	0.908 (0.378)	0.042 (0.018)	97.73 (3.12)	3.4
Lepidotrigla umbrosa	268.817 (58.626)	13.839 (3.002)	86.49 (0.49)	18.6
Leptomithrax weitei	0.3 (0.286)	0.001 (0.001)	100 (0)	0.5
Lethrinus genivittatus	6.934 (3.13)	0.078 (0.036)	132.14 (6.08)	2.9
Lobophora sp.	0.046 (0.044)	< 0.001		0.5
Lophiomus setigerus	8.563 (1.952)	0.154 (0.032)	100.24 (3.9)	15.2
Lophosquilla costata	0.077 (0.073)	0.007 (0.007)	21 (0)	0.5
Lovenia sp.	0.004 (0.004)	0.001 (0.001)	35 (0)	0.5
Luidia maculata	4.754 (1.884)	0.039 (0.014)	282.5 (61.25)	3.9
Lupocyclus philippinensis	0.361 (0.094)	0.08 (0.02)	21.85 (0.43)	11.3
Lupocyclus rotundatus	0.004 (0.004)	0.002 (0.002)	21 (0)	0.5
Lutjanus malabaricus	0.003 (0.003)	0.005 (0.005)	25 (0)	0.5
Lutjanus sebae	0.15 (0.142)	0.006 (0.006)	80 (0)	0.5
Lyreidus tridentatus	0.011 (0.01)	0.002 (0.001)	33 (6)	1
Macrorhamphosus molleri	0.008 (0.005)	0.003 (0.002)	76.67 (10.14)	1.5
Macrorhamphosus scolopax	0.038 (0.017)	0.009 (0.004)	68 (1.11)	2.5
Matuta inermis	0.625 (0.394)	0.063 (0.038)	26.54 (0.89)	2.9
Maxillicosta whitleyi	63.889 (12.813)	15.185 (3.076)	44.88 (0.19)	47.5
Melo georginae	1.64 (1.115)	0.011 (0.008)	107.5 (2.5)	1
Metapenaeopsis lamellata	0.04 (0.033)	0.006 (0.005)	14 (1)	1

Species	**Mean catch rate g ha^{-1}**	**Mean catch rate n ha^{-1}**	**Mean length mm**	**Frequency of capture (%)**
Metapenaeopsis palmensis	3.19 (0.808)	0.789 (0.203)	15.19 (0.24)	24.5
Metapenaeopsis provocatoria	0.003 (0.002)	0.008 (0.005)	7.7 (0.58)	2
Metapenaeopsis velutina	0.002 (0.002)	0.001 (0.001)	10 (1)	0.5
Metapenaeus bennettae	0.023 (0.022)	0.005 (0.005)	18 (0)	0.5
Metapenaeus ensis	0.039 (0.037)	0.005 (0.004)	23 (0)	0.5
Metasepia pfefferi	2.081 (0.604)	0.065 (0.018)	39.5 (2.88)	7.8
Microcanthus strigatus	0.931 (0.319)	0.026 (0.01)	100 (4.26)	4.4
Minous trachycephalus	0.007 (0.007)	0.003 (0.003)	35 (0)	0.5
Minous versicolor	1.199 (0.397)	0.053 (0.017)	74.09 (4.15)	4.9
Mollusc egg mass	1.568 (0.762)	0.009 (0.006)		2
Monacanthus chinensis	0.253 (0.186)	0.009 (0.007)	80 (0)	1
Muraenesox bagio	0.32 (0.305)	0.002 (0.002)	600 (0)	0.5
Mursia australiensis	0.04 (0.021)	0.005 (0.002)	35.5 (1.81)	2.5
Mustelus sp. *C*	0.272 (0.259)	0.002 (0.001)	377 (0)	0.5
Myra mammillaris	0.488 (0.371)	0.019 (0.014)	35.5 (0.5)	1
Nebrius ferrugineus	2.79 (1.968)	0.001 (0.001)		1
Nelusetta ayraudi	0.055 (0.052)	0.003 (0.003)	90 (0)	0.5
Nemipterus aurifilum	5.008 (1.177)	0.206 (0.046)	95.98 (1.17)	13.7
Nemipterus peronii	0.012 (0.011)	0.001 (0.001)	75 (0)	0.5
Nemipterus theodorei	610.756 (81.798)	12.325 (2.062)	121.16 (0.68)	70.1
Neomerinthe sp.	0.009 (0.006)	0.002 (0.001)	57.5 (2.5)	1
Neosebastes cf entaxis	0.01 (0.005)	0.004 (0.002)	36.25 (3.75)	2
Neosebastes incisipinnis	2.046 (0.859)	0.032 (0.013)	115 (15.3)	4.4
Octopus australis	4.808 (1.955)	0.066 (0.02)	39.81 (3.59)	7.8
Octopus exannulatus	0.022 (0.021)	0.002 (0.002)	30 (0)	0.5
Octopus kagoshimensis	5.776 (1.391)	0.092 (0.019)	45.08 (1.12)	12.7
Octopus marginatus	0.227 (0.151)	0.025 (0.017)	17.86 (3.04)	1.5
Octopus sp.	1.596 (0.605)	0.033 (0.01)	46.84 (3.69)	4.9
Octopus sp. *D*	0.001 (0.001)	< 0.001	25 (0)	0.5
Odontodactylus japonicus	0.297 (0.151)	0.015 (0.008)	24.43 (1.6)	2.9
Ophichthus sp.	0.808 (0.769)	0.003 (0.003)	690 (0)	0.5
Ophidion muraenolepis	0.049 (0.028)	0.003 (0.002)	131.67 (13.64)	1.5
Optivus sp. *1*	82.41 (10.229)	5.983 (0.743)	78.51 (0.22)	52.5
Oratosquilla nepa	0.081 (0.077)	0.006 (0.006)	24 (0)	0.5
Oratosquilla quinquedentata	0.826 (0.458)	0.022 (0.012)	34.75 (3.59)	1.5
Oratosquilla sp.	0.013 (0.012)	0.002 (0.002)	21 (0)	0.5
Oratosquilla woodmasoni	0.038 (0.036)	0.005 (0.005)	20 (0)	0.5
Orectolobus maculatus	1.094 (0.671)	0.005 (0.002)	330 (52.2)	1.5
Ostichthys japonicus	0.183 (0.122)	0.007 (0.004)	66.67 (19.22)	1.5
Pagrus auratus	0.424 (0.364)	0.006 (0.005)	117.5 (2.5)	1
Parabothus kiensis	0.018 (0.017)	0.002 (0.002)	100 (2.89)	0.5
Paracentropogon longispinis	0.188 (0.127)	0.012 (0.008)	72.5 (2.5)	1
Paramonacanthus lowei	1.235 (0.723)	0.032 (0.023)	92.5 (5.52)	1.5
Paramonacanthus otisensis	38.169 (6.257)	1.675 (0.287)	77.52 (0.95)	36.3
Parapercis binivirgata	0.031 (0.022)	0.002 (0.002)	125 (12.58)	1
Parapercis nebulosa	28.941 (5.009)	0.457 (0.08)	141.74 (2.58)	26
Parapercis sp. *A*	0.034 (0.033)	0.001 (0.001)	120 (0)	0.5
Paraplagusia unicolor	144.467 (29.243)	2.563 (0.552)	206.16 (0.95)	19.1
Parapriacanthus ransonneti	0.099 (0.055)	0.018 (0.01)	58.33 (1.67)	1.5
Pardachirus hedleyi	0.442 (0.303)	0.008 (0.005)	150 (0)	1
Parthenope longimanus	0.067 (0.054)	0.004 (0.003)	28.5 (4.5)	1
Parupeneus signatus	0.49 (0.32)	0.012 (0.007)	113.33 (20.88)	1.5
Parupeneus sp.	0.588 (0.365)	0.015 (0.009)	116.67 (12.63)	1.5
Pecten fumatus	0.686 (0.473)	0.012 (0.008)	62.5 (2.5)	1

Species	Mean catch rate g ha^{-1}	Mean catch rate n ha^{-1}	Mean length mm	Frequency of capture (%)
Pegasus volitans	9.923 (1.684)	1.644 (0.28)	113.53 (0.41)	23.5
Pelates sexlineatus	17.518 (7.48)	0.352 (0.118)	119.29 (2.2)	8.8
Pempheris affinis	0.089 (0.085)	0.004 (0.003)	95 (0)	0.5
Pentaceraster sp.	1.311 (1.054)	0.006 (0.005)	210 (20)	1
Peronella sp.	6.136 (1.687)	0.152 (0.033)	72.89 (4.84)	14.2
Petrarctus demani	0.49 (0.3)	0.04 (0.021)	23 (1.33)	2.9
Phalangipus australiensis	0.371 (0.105)	0.178 (0.062)	14.48 (0.63)	6.9
Phalangipus cf hystrix	0.01 (0.01)	0.003 (0.003)	20 (0)	0.5
Phalium areola	10.259 (4.071)	0.243 (0.093)	66.95 (1.17)	5.9
Phalium bandatum	4.385 (3.037)	0.121 (0.082)	64.72 (1.92)	1
Philine angasi	1.922 (1.143)	0.551 (0.348)	40.08 (0.9)	3.4
Photololigo sp.	38.488 (5.589)	1.117 (0.158)	82.7 (1.83)	43.6
Pilumnus hirsutus	0.144 (0.137)	0.012 (0.011)	40 (5)	0.5
Plagiopsetta glossa	0.696 (0.19)	0.026 (0.008)	158.1 (6.63)	6.9
Platycephalus arenarius	56.029 (16.897)	0.578 (0.133)	211.27 (3.23)	19.6
Platycephalus caeruleopunctatus	77.48 (14.431)	0.389 (0.08)	275.11 (4.06)	22.5
Platycephalus longispinis	301.145 (32.898)	11.152 (1.286)	142.09 (0.47)	64.2
Platycephalus marmoratus	0.43 (0.24)	0.003 (0.001)	261.67 (15.9)	1.5
Plesionika laurentae	1.519 (0.561)	0.415 (0.147)	16.4 (0.19)	11.8
Plotosus lineatus	53.125 (45.897)	2.026 (1.134)	92.87 (3.64)	13.2
Polycarpa sp.	0.028 (0.026)	0.002 (0.002)	45 (0)	0.5
Pomatomus saltatrix	6.906 (2.724)	0.049 (0.017)	186.88 (14.45)	3.9
Portunus argentatus	82.664 (17.305)	21.201 (4.506)	31.87 (0.12)	49.5
Portunus haanii	0.728 (0.311)	0.034 (0.013)	51.88 (6.38)	3.4
Portunus orbitosinus	0.543 (0.179)	0.128 (0.042)	26 (0.78)	5.4
Portunus pelagicus	74.762 (11.117)	1.007 (0.229)	94.46 (2.45)	26
Portunus rubromarginatus	215.207 (17.098)	15.367 (1.702)	44.33 (0.18)	84.3
Portunus sanguinolentus	58.195 (15.598)	1.342 (0.372)	86.86 (1.46)	16.2
Priacanthus macracanthus	2.676 (1.132)	0.02 (0.008)	162.14 (17.89)	3.4
Prionocidaris sp.	75.689 (13.314)	1.881 (0.277)	34.3 (0.32)	48
Pristigenys niphonia	0.149 (0.104)	0.005 (0.003)	68.33 (24.89)	1.5
Pristotis jerdoni	0.544 (0.268)	0.043 (0.02)	65 (8.13)	2.5
Psettina gigantea	1.254 (0.256)	0.162 (0.03)	89.19 (1.64)	18.6
Psettina iijimai	0.103 (0.035)	0.041 (0.014)	63.75 (1.41)	5.4
Psettina sp.	0.02 (0.014)	0.007 (0.005)	65 (2.89)	1.5
Pseudorhombus argus	0.23 (0.219)	0.005 (0.004)	180 (0)	0.5
Pseudorhombus arsius	47.639 (8.596)	0.374 (0.065)	217.6 (4.46)	17.6
Pseudorhombus diplospilus	0.081 (0.077)	0.002 (0.002)	160 (0)	0.5
Pseudorhombus dupliciocellatus	24.407 (4.282)	0.525 (0.068)	149.66 (4.29)	31.4
Pseudorhombus jenynsii	4.854 (1.805)	0.054 (0.019)	197.5 (7.24)	3.9
Pseudorhombus sp.	0.006 (0.006)	0.001 (0.001)	117.5 (17.5)	0.5
Pseudorhombus spinosus	1.1 (0.463)	0.04 (0.016)	144 (7.56)	2.9
Pseudorhombus tenuirastrum	119.628 (10.888)	1.931 (0.188)	194.12 (0.94)	60.8
Pterois volitans	0.27 (0.143)	0.023 (0.012)	70 (3.87)	2
Quollastria gonypetes	1.045 (0.232)	0.135 (0.031)	20.29 (0.28)	13.7
Rabdosargus sarba	0.567 (0.54)	0.008 (0.008)	120 (5)	0.5
Randallia eburnea	0.009 (0.009)	0.001 (0.001)	21 (0)	0.5
Rapana rapiformis	1.024 (0.633)	0.023 (0.014)	60 (2.04)	1.5
Ratabulus diversidens	45.214 (7.655)	0.543 (0.08)	180.4 (3.41)	30.9
Rhinopias frondosa	0.822 (0.783)	0.009 (0.009)	130 (0)	0.5
Rogadius patriciae	0.196 (0.12)	0.022 (0.013)	83.75 (3.15)	1.5
Samaris macrolepis	0.251 (0.118)	0.012 (0.005)	121.82 (7.02)	2.9

Species	Mean catch rate g ha^{-1}	Mean catch rate n ha^{-1}	Mean length mm	Frequency of capture (%)
Sargassum sp.	0.293 (0.216)			1
Saurida filamentosa	43.933 (11.944)	1.094 (0.391)	159.54 (2.59)	20.1
Saurida grandisquamis	770.875 (79.153)	4.809 (0.545)	253.59 (2.2)	77
Scomber australisicus	0.546 (0.415)	0.005 (0.003)	181.67 (9.28)	1.5
Scorpaena cardinalis	0.362 (0.205)	0.006 (0.003)	115 (2.89)	1.5
Scorpaenopsis brevifrons	0.037 (0.035)	0.002 (0.002)	60 (0)	0.5
Scylla serrata	0.873 (0.831)	0.001 (0.001)	188 (0)	0.5
Scyllarus sp. *A*	0.014 (0.013)	0.003 (0.003)	17.25 (0.95)	0.5
Scyphozoa	3.769 (3.316)	0.008 (0.005)	200 (80)	1
Sea pen	0.59 (0.562)	0.003 (0.003)	220 (0)	0.5
Sea star	0.553 (0.481)	0.022 (0.013)	70.71 (8.24)	1.5
Sea star 103	0.069 (0.066)	0.005 (0.005)	100 (0)	0.5
Sea star 3	0.061 (0.05)	0.005 (0.003)	103.33 (29.2)	1.5
Sea star 6	2.351 (1.969)	0.054 (0.046)	127.78 (2.52)	1
Sea star 71	0.005 (0.005)	0.004 (0.004)	85 (0)	0.5
Sea star 77	1.803 (1.717)	0.011 (0.01)	135 (0)	0.5
Sea Urchin 105	0.101 (0.097)	0.006 (0.005)	55 (0)	0.5
Sea Urchin 2	0.013 (0.013)	0.001 (0.001)	40 (0)	0.5
Sea Urchin 3	2.268 (1.131)	0.045 (0.019)	47.11 (4.69)	2.9
Sea Urchin 6	0.645 (0.354)	0.114 (0.068)	28.65 (1.59)	3.4
Sea Urchin 67	0.08 (0.054)	0.006 (0.004)	47.5 (7.5)	1
Sea Urchin 68	0.606 (0.235)	0.034 (0.012)	41.74 (2.85)	5.9
Sea Urchin 70	0.103 (0.098)	0.006 (0.006)	42.5 (5.73)	0.5
Sea Urchin 71	0.038 (0.036)	0.001 (0.001)	95 (0)	0.5
Sepia limata	0.404 (0.086)	0.092 (0.021)	32.82 (0.43)	14.2
Sepia mira	0.077 (0.073)	0.011 (0.01)	45 (0)	0.5
Sepia opipara	1.923 (0.437)	0.043 (0.009)	69.18 (2.94)	11.8
Sepia papuensis	0.038 (0.028)	0.007 (0.005)	33.33 (3.33)	1.5
Sepia plangon	100.407 (12.878)	3.62 (0.404)	58.61 (0.59)	61.8
Sepia rex	0.006 (0.006)	0.001 (0.001)	31.67 (1.67)	0.5
Sepia rozella	0.734 (0.421)	0.012 (0.006)	67.5 (10.26)	3.9
Sepia smithi	6.771 (2.283)	0.254 (0.098)	50.3 (2.63)	7.4
Sepia whitleyana	13.631 (4.238)	0.576 (0.187)	48.6 (1.99)	7.4
Sepioloidea lineolata	1.886 (0.507)	0.133 (0.032)	32.01 (0.87)	10.3
Sicyonia cristata	0.547 (0.127)	0.12 (0.027)	14.3 (0.43)	12.7
Siganus fuscescens	0.104 (0.099)	0.005 (0.004)	90 (0)	0.5
Sillago ciliata	0.503 (0.479)	0.005 (0.005)	190 (0)	0.5
Sillago flindersi	1.057 (0.441)	0.017 (0.008)	163 (3.96)	4.4
Sillago maculata	0.17 (0.162)	0.005 (0.005)	135 (0)	0.5
Sillago robusta	690.89 (98.126)	20.599 (3.043)	130.91 (0.67)	38.7
Solegnathus dunckeri	0.008 (0.007)	0.007 (0.007)	122.5 (7.5)	0.5
Solegnathus hardwickii	0.258 (0.082)	0.045 (0.014)	212 (11.98)	5.9
Soleichthys heterorhinos	0.352 (0.236)	0.011 (0.008)	132.5 (7.5)	1
Solenocera bifurcata	0.103 (0.034)	0.03 (0.009)	16.95 (0.68)	5.4
Solenocera choprai	0.153 (0.045)	0.056 (0.016)	15.47 (0.39)	6.9
Sorsogona tuberculata	0.537 (0.175)	0.05 (0.017)	83.33 (2.56)	4.9
Sphenopus marsupialus	16.163 (5.387)	0.642 (0.195)	42.05 (1.1)	8.3
Spondylus wrightianus	0.711 (0.417)	0.013 (0.008)	59.6 (2.07)	1.5
Stellaster sp.	0.035 (0.028)	0.003 (0.002)	70 (0)	1
Sympagurus sp.	0.013 (0.006)	0.006 (0.003)	12.25 (1)	2.9
Synagrops japonicus	0.06 (0.049)	0.004 (0.003)	88.75 (4.27)	1
Synchiropus rameus	32.255 (7.622)	1.21 (0.262)	99.3 (1.11)	27.5
Synodus hoshinonis	1.546 (0.621)	0.032 (0.01)	144.38 (5.95)	6.4
Synodus macrops	0.018 (0.017)	0.001 (0.001)	145 (0)	0.5

Species	**Mean catch rate g ha^{-1}**	**Mean catch rate n ha^{-1}**	**Mean length mm**	**Frequency of capture (%)**
Temnopleurus sp.	0.03 (0.029)	0.002 (0.002)	47.5 (2.5)	0.5
Tetrosomus concatenatus	111.307 (21.362)	3.116 (0.511)	73.26 (1.32)	54.9
Thalamita sima	0.11 (0.071)	0.012 (0.008)	34 (2.08)	1.5
Thamnaconus hypargyreus	0.196 (0.137)	0.01 (0.006)	87.69 (3.03)	2
Thamnaconus tessellatus	0.018 (0.018)	0.001 (0.001)	100 (0)	0.5
Tonna chinensis	0.156 (0.149)	0.004 (0.004)	71.4 (1.62)	0.5
Tonna tetracotula	3.632 (1.888)	0.038 (0.017)	86.36 (8.29)	3.4
Tonna variegata	4.825 (2.873)	0.03 (0.018)	116.43 (8.84)	2.5
Torquigener altipinnis	73.989 (12.006)	2.81 (0.451)	80.73 (0.68)	37.7
Torquigener pallimaculatus	1.65 (1.084)	0.059 (0.037)	82 (3.68)	2.5
Torquigener perlevis	5.736 (1.709)	0.08 (0.02)	110.94 (6.34)	7.4
Torquigener pleurogramma	2.289 (0.988)	0.052 (0.022)	101.33 (2.56)	2.5
Torquigener sp.	0.002 (0.001)	0.002 (0.001)	28.33 (3.33)	1.5
Trachinocephalus myops	105.497 (12.1)	2.427 (0.311)	135.46 (1.32)	55.4
Trachurus novaezelandiae	96.797 (33.384)	1.855 (0.657)	143.75 (0.67)	10.8
Trachypenaeus curvirostris	81.864 (15.38)	22.725 (4.284)	16.2 (0.08)	78.4
Tragulichthys jaculiferus	0.463 (0.441)	0.002 (0.002)	140 (0)	0.5
Tricanthodes sp.	0.036 (0.034)	0.004 (0.003)	60 (0)	0.5
Tripodichthys angustifrons	1.363 (1.298)	0.01 (0.01)	180 (15)	0.5
Trygonoptera testacea	98.387 (22.236)	0.75 (0.173)	218.94 (5.9)	20.1
Trygonorrhina sp. *A*	1.14 (0.7)	0.005 (0.002)	344 (45.65)	1.5
Unidentified Ascidian	2.454 (1.081)	0.045 (0.017)	58.57 (4.97)	3.4
Unidentified Bivalve	0.012 (0.012)	0.001 (0.001)	38 (0)	0.5
Unidentified Crinoid	2.766 (0.997)	0.066 (0.023)	380 (0)	5.9
Unidentified Gorgonian	0.014 (0.013)	0.001 (0.001)		0.5
Unidentified Hydroid	0.687 (0.491)	0.004 (0.004)	131.96 (2.19)	2
Unidentified Polychaete	0.036 (0.034)	0.004 (0.004)		0.5
Unidentified Sponge	2.17 (0.911)	0.004 (0.002)		3.4
Unidentified Stomatopod	0.143 (0.136)	0.012 (0.011)	24.5 (0.5)	0.5
Upeneichthys lineatus	15.164 (5.293)	0.188 (0.058)		11.8
Upeneus asymmetricus	85.648 (17.32)	3.075 (0.646)	107.05 (0.51)	24
Upeneus tragula	32.185 (5.503)	1.292 (0.221)	96.52 (0.67)	38.2
Uranoscopus terraereginae	1.54 (0.92)	0.032 (0.011)	75.88 (9.3)	5.9
Urolophus kapalensis	20.346 (9.54)	0.102 (0.043)	261.03 (6.19)	8.3
Valenciennea sp.	0.117 (0.092)	0.008 (0.005)	95 (10)	1
Vepricardium multispinosum	0.272 (0.259)	0.005 (0.005)	55 (0)	0.5
Xenophora peroniana	0.499 (0.172)	0.028 (0.009)	65.75 (3.69)	4.9
Zanclistius elevatus	1.167 (1.111)	0.003 (0.003)	240 (0)	0.5
Zebrias craticula	0.772 (0.444)	0.012 (0.006)	163.33 (6.67)	1.5
Zebrias scalaris	8.255 (2.171)	0.208 (0.054)	144.76 (1.8)	12.7
Zeus faber	0.019 (0.013)	0.003 (0.002)	50 (0)	1

Appendix 2. List of 525 taxa in the bycatch of the north Queensland tiger/endeavour prawn trawl fishery based on bycatch sub-samples from 418 individual net trawls from the research charter and opportunistically sampling the fleet between February 2001 and November 2002. Mean catch rates are in grams and numbers per hectare, mean lengths (mm) are fork length or standard length for fish, carapace length for crustaceans, disc width or length for elasmobranchs, total length for echinoderms, and shell length for molluscs. Includes small or undersized principal target and permitted species. Frequency is percentage of occurrence in the 418 net trawls. Standard error in brackets.

Species	**Mean catch rate g ha^{-1}**	**Mean catch rate n ha^{-1}**	**Mean length mm**	**Frequency of capture (%)**
Abalistes stellaris	0.014 (0.014)	0.001 (0.001)	60 (0)	0.2
Absalom radiatus	0.01 (0.008)	0.007 (0.005)	53 (7)	0.5
Acanthocepola limbata	0.016 (0.016)	< 0.001	270 (0)	0.2
Acentrogobius caninus	1.717 (0.447)	0.09 (0.021)	97.66 (3.8)	7.2
Acentrogobius sp.	2.01 (0.485)	0.134 (0.028)	94.03 (4.98)	8.6
Adventor elongatus	0.648 (0.15)	0.051 (0.011)	82.8 (1.83)	9.6
Aesopia cornuta	0.004 (0.004)	0.001 (0.001)	90 (0)	0.2
Alectis ciliaris	0.091 (0.046)	0.021 (0.011)	59.2 (4.29)	1.2
Alectis indicus	0.039 (0.028)	0.006 (0.004)	68.5 (2.5)	0.5
Amblygaster sirm	0.011 (0.011)	0.001 (0.001)	80 (0)	0.2
Amusium pleuronectes	59.985 (5.672)	5.328 (0.472)	50.87 (0.31)	79.4
Anacanthus barbatus	0.181 (0.075)	0.02 (0.006)	150.29 (12.67)	3.3
Anchisomus multistriatus	0.143 (0.085)	0.005 (0.003)	88.67 (9.84)	0.7
Anodontostoma chacunda	0.053 (0.053)	< 0.001	160 (0)	0.2
Antigonia lamellaris	0.011 (0.011)	0.002 (0.002)	24 (0)	0.2
Apistops caloundra	1.657 (0.971)	0.155 (0.094)	92.23 (2.63)	1.4
Apistus carinatus	16.565 (2.156)	1.257 (0.136)	75.09 (1.16)	52.6
Apogon albimaculosus	0.011 (0.006)	0.001 (0.001)	55 (5.4)	1
Apogon brevicaudatus	5.309 (1.568)	0.451 (0.138)	76.69 (1.33)	13.6
Apogon capricornis	0.262 (0.09)	0.118 (0.041)	51.5 (4.22)	2.9
Apogon carinatus	0.212 (0.212)	0.011 (0.011)	110 (0)	0.2
Apogon ellioti	36.976 (3.096)	3.962 (0.323)	67.74 (0.9)	89.2
Apogon fasciatus	104.632 (8.335)	13.828 (1.221)	65.12 (0.59)	89
Apogon melanopus	3.107 (1.312)	0.207 (0.086)	96.48 (4.31)	2.9
Apogon moluccensis	0.021 (0.021)	0.001 (0.001)	90 (0)	0.2
Apogon nigripinnis	0.756 (0.251)	0.082 (0.029)	56.75 (3.39)	6.2
Apogon poecilopterus	58.076 (6.632)	5.508 (0.603)	69.83 (0.87)	86.4
Apogon robustus	2.636 (1.616)	0.431 (0.267)	71.33 (0.31)	1.2
Apogon semilineata	0.417 (0.113)	0.067 (0.017)	61.91 (1.81)	6.2
Apogon septemstriatus	0.698 (0.184)	0.262 (0.06)	42.42 (2.03)	10.5
Archaster typicus	0.002 (0.002)	0.003 (0.003)	34 (0)	0.2
Argyrops spinifer	0.228 (0.212)	0.004 (0.003)	80.63 (23.73)	1
Ariosoma anago	0.04 (0.04)	< 0.001	460 (0)	0.2
Arius thalassinus	3.143 (0.813)	0.141 (0.045)	139.39 (5.18)	5.5
Arnoglossus waitei	0.881 (0.154)	0.122 (0.018)	81.97 (2.02)	16.5
Arothron aerostaticus	0.378 (0.359)	0.004 (0.003)	86.25 (31.25)	0.5
Arothron manillensis	0.212 (0.133)	0.023 (0.014)	63.63 (5.86)	1
Arothron reticularis	0.06 (0.06)	0.003 (0.003)	98 (0)	0.2
Arothron stellatus	1.025 (1.025)	0.005 (0.005)	155 (0)	0.2
Arotrolepis filicauda	0.014 (0.006)	0.009 (0.003)	30 (3.27)	1.9
Aseraggodes macleayanus	0.017 (0.017)	0.001 (0.001)	100 (0)	0.2
Asterorhombus intermedius	0.284 (0.074)	0.02 (0.006)	102.03 (2.41)	3.8
Astropecten sp.	< 0.001	< 0.001	35 (0)	0.2
Astropeten monacanthus	0.006 (0.006)	0.004 (0.004)	46 (0)	0.2

Species	**Mean catch rate g ha^{-1}**	**Mean catch rate n ha^{-1}**	**Mean length mm**	**Frequency of capture (%)**
Atherinomorus ogilbyi	0.271 (0.087)	0.023 (0.007)	87.75 (2.26)	2.9
Boodlea sp	0.009 (0.006)	0.009 (0.006)	55.5 (21.5)	0.5
Brachypterois serrulatus	0.016 (0.016)	0.001 (0.001)	75 (0)	0.2
Bregmaceros japonicus	0.017 (0.009)	0.01 (0.004)	48.38 (5.05)	1.9
Calappa lophus	0.089 (0.089)	0.002 (0.002)	59 (0)	0.2
Callinectes madagascaninensis	0.029 (0.029)	0.002 (0.002)	42 (0)	0.2
Callionymus belcheri	6.307 (0.703)	0.829 (0.084)	83.96 (1.24)	51
Callionymus filamentosus	0.149 (0.108)	0.013 (0.01)	127 (2)	0.5
Callionymus goodladi	0.947 (0.676)	0.071 (0.049)	150.3 (7.65)	0.7
Callionymus grossi	38.397 (3.223)	2.341 (0.219)	125.29 (1.03)	73.7
Callionymus limiceps	12.425 (2.663)	2.066 (0.455)	106.77 (1.77)	15.1
Callionymus meridionalis	0.276 (0.176)	0.028 (0.013)	114.2 (21.87)	1.2
Callionymus semeiophor	0.007 (0.007)	< 0.001	130 (0)	0.2
Callionymus superbus	0.091 (0.065)	0.007 (0.005)	188 (13)	0.5
Callionymus whitheadi	4.33 (0.938)	0.671 (0.145)	109.95 (2.86)	8.9
Canthigaster bennetti	0.059 (0.059)	0.006 (0.006)	75 (0)	0.2
Canthigaster compressa	0.023 (0.011)	0.005 (0.003)	54.7 (1.89)	1.2
Carangoides caeruleopinnatus	0.008 (0.008)	0.003 (0.003)	55 (0)	0.2
Carangoides chrysophrys	0.498 (0.277)	0.005 (0.002)	148.07 (6.38)	1.2
Carangoides gymnostethus	0.023 (0.023)	< 0.001	180 (0)	0.2
Carangoides hedlandensis	0.401 (0.226)	0.004 (0.002)	144.38 (8.61)	1
Carangoides humerosus	4.035 (1.269)	0.04 (0.009)	149.66 (6.87)	8.9
Carangoides talamparoides	1.093 (0.355)	0.013 (0.004)	136.67 (9.96)	4.3
Caranx bucculentus	1.168 (0.471)	0.035 (0.011)	87.19 (13.38)	3.8
Caranx para	0.104 (0.104)	0.003 (0.003)	131 (0)	0.2
Caranx sexfasciatus	0.448 (0.275)	0.008 (0.005)	122.78 (8.94)	0.7
Carcharhinus melanopterus	0.221 (0.156)	< 0.001		0.5
Carcharhinus tilstoni	0.467 (0.467)	< 0.001	770 (0)	0.2
Carcinoplax sp.	0.003 (0.003)	0.001 (0.001)	13 (0)	0.2
Carinosquilla multicarinata	0.164 (0.074)	0.01 (0.004)	25.4 (1.52)	2.4
Caulastrea sp.	0.008 (0.008)	0.003 (0.003)	18 (0)	0.2
Centriscus scutatus	0.084 (0.016)	0.119 (0.019)	85.71 (2.52)	13.4
Centrogenys vaigiensis	0.48 (0.187)	0.036 (0.014)	76.87 (4.45)	2.4
Cephalopholis pachycentron	0.059 (0.059)	0.003 (0.003)	104 (0)	0.2
Cepola shlegelii	0.168 (0.067)	0.006 (0.003)	285 (31.74)	1.7
Ceratoplax sp.	0.024 (0.024)	0.001 (0.001)	40 (0)	0.2
Ceratosoma sp.	0.021 (0.021)	0.006 (0.006)	53 (0)	0.2
Ceratothoa sp.	0.015 (0.015)	0.012 (0.012)	33.5 (0)	0.2
Chaetodermis penicilligris	1.163 (0.52)	0.028 (0.013)	131.78 (10.67)	1.4
Chaetodontoplus duboulayi	0.102 (0.102)	0.004 (0.004)	96 (0)	0.2
Charybdis bimaculata	0.113 (0.054)	0.013 (0.006)	34.8 (0.64)	1.2
Charybdis cruciata	0.418 (0.265)	0.007 (0.004)	69 (18.22)	1
Charybdis feriatus	0.197 (0.145)	0.002 (0.001)	97 (29)	0.5
Charybdis jaubertensis	0.253 (0.085)	0.016 (0.005)	37.59 (1.16)	4.3
Charybdis miles	0.078 (0.035)	0.007 (0.003)	35.33 (1.28)	1.4
Charybdis natator	0.971 (0.363)	0.018 (0.008)	66.22 (4.33)	2.2
Charybdis truncata	144.688 (15.222)	9.886 (0.933)	37.69 (0.29)	88.3
Charybdis yaldwyni	0.005 (0.005)	0.003 (0.003)	21 (0)	0.2
Cheilopogon pinnatibarbatus	0.182 (0.088)	0.021 (0.006)	68.57 (7.17)	3.6
Cheilopogon suttoni	0.068 (0.04)	0.01 (0.006)	91.67 (3.38)	0.7
Chiloscyllium punctatum	0.644 (0.347)	0.006 (0.003)	307.6 (46.81)	1.2
Chlamys leopardus	2.286 (0.525)	0.16 (0.047)	48.1 (1.67)	9.1
Chlamys sp.	0.942 (0.638)	0.064 (0.044)	46.97 (0.98)	0.7
Choerodon cephalotes	39.427 (6.665)	1.016 (0.189)	122.67 (1.96)	20.1

Species	**Mean catch rate g ha^{-1}**	**Mean catch rate n ha^{-1}**	**Mean length mm**	**Frequency of capture (%)**
Choerodon monostigma	1.983 (0.825)	0.058 (0.021)	115.85 (8.28)	2.6
Choerodon peniciligera	0.043 (0.043)	0.001 (0.001)	125 (0)	0.2
Choerodon rubescens	0.341 (0.341)	0.011 (0.011)	114 (0)	0.2
Choerodon shoenleinii	0.044 (0.044)	0.003 (0.003)	97 (0)	0.2
Choerodon sp. *1*	0.151 (0.151)	0.011 (0.011)	88.75 (0)	0.2
Choerodon sp. *2*	7.31 (1.697)	0.453 (0.111)	101.83 (2.3)	11
Choerodon sugillatum	1.87 (0.415)	0.066 (0.015)	100.49 (2.03)	6.9
Choerodon venustus	0.065 (0.065)	0.004 (0.004)	102 (0)	0.2
Choerodon zamboangae	0.122 (0.122)	0.006 (0.006)	95.5 (0)	0.2
Cirrhipathes sp.	0.095 (0.042)	0.072 (0.024)	334.76 (40.21)	3.3
Clibanarius sp.	0.05 (0.023)	0.011 (0.004)	10.73 (1.18)	3.1
Cociella crocodila	0.106 (0.075)	0.012 (0.008)	111.5 (9.5)	0.5
Coradion chrysozonus	0.269 (0.141)	0.024 (0.011)	62.9 (4.77)	1.2
Corbula sp.	0.013 (0.013)	0.003 (0.003)	24 (0)	0.2
Crossorhombus azureus	0.051 (0.037)	0.005 (0.004)	101.5 (13.5)	0.5
Cryptocentrus cinctus	0.068 (0.068)	0.003 (0.003)	140 (0)	0.2
Cryptocentrus sp.	0.007 (0.007)	0.001 (0.001)	80 (0)	0.2
Cryptopodia spatulifrons	0.014 (0.008)	0.01 (0.007)	34.5 (3.67)	0.7
Ctenotrypauchen microcephalus	0.004 (0.004)	0.002 (0.002)	65 (0)	0.2
Cuspidaria sp.	0.012 (0.012)	0.003 (0.003)	22 (0)	0.2
Cyclichthys orbicularis	2.315 (0.904)	0.035 (0.015)	101.39 (10.23)	2.2
Cymbacephalus bosschei	0.565 (0.565)	0.029 (0.029)	165.5 (0)	0.2
Cymbacephalus nematophthalmus	0.81 (0.291)	0.017 (0.006)	161.36 (12.29)	2.6
Cynoglossus kopsi	0.517 (0.109)	0.036 (0.007)	117.63 (1.71)	7.2
Cypselurus sp.	0.004 (0.004)	0.001 (0.001)	55 (0)	0.2
Cystoseria sp.	0 (0)	0.003 (0.003)	42 (0)	0.2
Dactyloptena macracanthus	0.09 (0.054)	0.01 (0.006)	83 (6.56)	0.7
Dactyloptena papilio	0.332 (0.113)	0.022 (0.007)	86.42 (8.23)	4.3
Dactylopus dactylopus	16.21 (2.605)	0.995 (0.162)	110.2 (2.62)	30.4
Dardanus sp. *1*	0.082 (0.049)	0.031 (0.018)	11.69 (0.61)	1
Dasyatis kuhlii	0.865 (0.548)	0.002 (0.001)	210 (0)	1
Dasyatis leylandi	0.321 (0.177)	0.002 (0.001)	274.2 (67.44)	1.2
Dendrochirus zebra	0.22 (0.22)	0.003 (0.003)	179 (0)	0.2
Dendronephthya sp.	0.068 (0.044)	0.016 (0.01)	47.67 (5.36)	0.7
Dendrophysa russelli	0.832 (0.832)	0.006 (0.006)	174 (0)	0.2
Dexillichthys mulleri	3.926 (0.999)	0.049 (0.008)	162.1 (4.81)	14.1
Diagramma pictum	30.129 (6.986)	0.998 (0.208)	99.79 (2.68)	36.6
Dictyosquilla foveolata	0.143 (0.088)	0.004 (0.002)	32.75 (5.57)	1
Diodon hystrix	0.045 (0.045)	0.004 (0.004)	48 (0)	0.2
Dollabella auricularia	0.023 (0.023)	0.003 (0.003)	43 (0)	0.2
Dosinia sp.	0.005 (0.005)	0.003 (0.003)	20 (0)	0.2
Dromidia sp.	0.041 (0.04)	0.006 (0.005)	38 (31)	0.5
Dussumieria elopsoides	0.051 (0.04)	0.001 (0.001)	147.5 (2.5)	0.5
Echeneis naucrates	0.05 (0.05)	< 0.001	310 (0)	0.2
Echinocardium sp.	0.093 (0.093)	0.007 (0.007)	44 (0)	0.2
Elates ransonetti	2.839 (0.328)	0.327 (0.038)	136.87 (1.56)	35.2
Engyprosopon grandisquama	3.38 (0.77)	0.379 (0.069)	85.48 (1.35)	19.6
Epinephelus sexfasciatus	16.119 (2.742)	0.24 (0.034)	137.12 (2.75)	27.3
Epizoanthus sp.	0.04 (0.036)	0.009 (0.005)	467.67 (379.68)	0.7
Eucrate dorsalis	0.01 (0.009)	0.003 (0.002)	16 (6)	0.5
Eucrate sp. *2*	0.002 (0.002)	0.003 (0.002)	11 (1)	0.5
Euprymna sp. *C*	0.011 (0.005)	0.003 (0.001)	20 (0.93)	1.4
Euprymna tasmanica	0.101 (0.021)	0.035 (0.007)	16.63 (0.7)	7.7
Euristhmus nudiceps	50.187 (4.862)	1.922 (0.218)	231.63 (1.86)	57.9

Species	**Mean catch rate g ha^{-1}**	**Mean catch rate n ha^{-1}**	**Mean length mm**	**Frequency of capture (%)**
Filicampus tigris	0.016 (0.012)	0.003 (0.002)	265 (10)	0.5
Fillimanus heptadactyla	0.797 (0.413)	0.033 (0.023)	163.5 (13.74)	1
Fistularia petimba	6.683 (0.755)	0.424 (0.038)	304.05 (4.52)	41.1
Fragum sp.	0.002 (0.002)	0.003 (0.003)	13 (0)	0.2
Galathea sp.	0 (0)	0.001 (0.001)	5 (0)	0.2
Gazza minuta	1.118 (0.353)	0.034 (0.011)	102.05 (3.89)	5.5
Gerres filamentosus	7.236 (2.228)	0.223 (0.055)	104.7 (1.88)	19.9
Gerres macrosoma	0.006 (0.006)	< 0.001	90 (0)	0.2
Gerres subfasciatus	7.709 (1.575)	0.175 (0.034)	122.23 (2.67)	12.7
Glaucosoma magnificum	1.791 (1.103)	0.097 (0.059)	90.66 (1.8)	1.4
Gnathanodon speciosus	0.019 (0.014)	0.005 (0.005)	82 (18)	0.5
Goniadiscaster sp.	0.005 (0.005)	0.002 (0.002)	42 (0)	0.2
Grammatobothus pennatus	0.028 (0.018)	0.002 (0.001)	113.33 (1.67)	0.7
Grammatobothus polyophthalmus	3.607 (0.487)	0.274 (0.035)	105.31 (2.16)	28.9
Gymnocranius griseus	4.62 (3.339)	0.474 (0.346)	79.34 (1.17)	0.7
Halimeda discoidea	0.516 (0.391)	0.049 (0.019)	98.56 (16.21)	2.2
Halimeda sp.	0.597 (0.224)	0.057 (0.023)	94.77 (10.78)	3.6
Harpiosquilla harpax	0.165 (0.069)	0.003 (0.001)	39.93 (2.65)	1.7
Hemigaleus australiensis	0.51 (0.417)	0.001 (0.001)	453.75 (145.45)	1
Hemiscyllium ocellatum	0.111 (0.111)	< 0.001		0.2
Herklotsichthys koningsbergeri	0.148 (0.103)	0.005 (0.003)	117.25 (7.25)	1
Herklotsichthys lippa	0.216 (0.086)	0.013 (0.005)	102.58 (7.07)	1.9
Himantura toshi	4.415 (4.164)	0.002 (0.001)	290.8 (53.81)	1.2
Hippocampus queenslandicus	0.001 (0.001)	0.001 (0.001)	55 (0)	0.2
Holothuria nobilils	0.282 (0.282)	0.007 (0.007)	110.5 (0)	0.2
Holothuria ocellata	0.08 (0.061)	0.002 (0.002)	125 (25)	0.5
Hyastenus sp.	0.007 (0.007)	0.001 (0.001)	25 (0)	0.2
Hyporhamphus (Reporhamphus) dussumieri	0.267 (0.151)	0.012 (0.006)	193.5 (28.07)	1
Hyporhamphus (Reporhamphus) quoyi	0.103 (0.103)	0.003 (0.003)	208 (0)	0.2
Ichthyscopus fasciatus	0.212 (0.212)	0.001 (0.001)	160 (0)	0.2
Ilisha sp.	0.009 (0.009)	0.005 (0.005)	62 (0)	0.2
Inegocia harrisii	0.074 (0.074)	0.003 (0.003)	147 (0)	0.2
Inegocia japonica	106.664 (6.598)	4.935 (0.277)	128.23 (0.98)	88
Inimicus caledonicus	0.3 (0.095)	0.02 (0.006)	75.14 (3.46)	4.3
Inimicus didactylus	0.063 (0.063)	0.003 (0.003)	104 (0)	0.2
Inimicus sinensis	0.252 (0.147)	0.018 (0.01)	89.88 (3.85)	1
Ixa inermis	0.001 (0.001)	< 0.001	50 (0)	0.2
Johnius (Johnieops) borneensis	8.141 (1.186)	0.159 (0.021)	128.52 (2.76)	17.2
Johnius amblycephalus	2.009 (0.479)	0.031 (0.007)	146.69 (2.4)	5
Johnius coitor	0.183 (0.183)	0.003 (0.003)	182 (0)	0.2
Jonas luteanus	0.024 (0.024)	0.003 (0.003)	37 (0)	0.2
Kanekonia queenslandica	0.101 (0.059)	0.01 (0.005)	71.75 (14.04)	1
Kumococius rodericensis	3.097 (1.494)	0.215 (0.098)	122.45 (5.86)	1.2
Lactarius lactarius	0.526 (0.249)	0.012 (0.007)	147.1 (4.57)	1.2
Lactoria cornuta	1.668 (0.47)	0.046 (0.011)	75.04 (6.2)	6.2
Lactoria diaphana	0.101 (0.086)	0.008 (0.006)	54 (14)	0.5
Laganum depressum	0.519 (0.244)	0.081 (0.019)	36.73 (6.42)	4.8
Lagocephalus lunaris	0.062 (0.062)	0.001 (0.001)	110 (0)	0.2
Lagocephalus sceleratus	77.848 (8.949)	2.903 (0.346)	113.52 (0.75)	80.1
Lagocephalus spadiceus	0.555 (0.196)	0.053 (0.033)	96.57 (9.82)	3.6
Leiognathus aureus	0.027 (0.027)	0.02 (0.02)	48.43 (0)	0.2
Leiognathus bindus	3.804 (0.484)	0.616 (0.168)	61.89 (0.98)	34.2
Leiognathus blochii	0.064 (0.042)	0.005 (0.004)	83.15 (9.78)	0.7

Species	**Mean catch rate g ha^{-1}**	**Mean catch rate n ha^{-1}**	**Mean length mm**	**Frequency of capture (%)**
Leiognathus decorus	6.805 (1.589)	1.593 (0.511)	73.88 (1.67)	14.1
Leiognathus elongatus	0.146 (0.112)	0.006 (0.004)	115 (16)	0.5
Leiognathus equulus	7.2 (3.397)	0.115 (0.055)	121.33 (3.17)	8.9
Leiognathus leuciscus	13.226 (2.447)	0.668 (0.104)	89.78 (1.2)	30.6
Leiognathus moretoniensis	4.451 (0.734)	0.758 (0.134)	59.83 (1.92)	15.3
Leiognathus smithursti	0.211 (0.126)	0.012 (0.009)	99.33 (12.37)	0.7
Leiognathus sp. *2*	10.847 (1.73)	1.601 (0.256)	65.92 (1.13)	30.4
Leiognathus splendens	43.225 (12.784)	2.717 (0.732)	87.72 (1.59)	19.6
Lepidotrigla argus	1.777 (0.529)	0.097 (0.029)	102.55 (3.35)	5.7
Lethrinus genivittatus	45.487 (12.099)	1.54 (0.413)	113.22 (1.83)	19.4
Lethrinus semicinctus	56.51 (26.898)	3.443 (1.873)	118.77 (2.42)	11
Lethrinus sp. *3*	0.42 (0.42)	0.003 (0.003)	210 (0)	0.2
Lethrinus variegatus	0.056 (0.056)	0.003 (0.003)	108 (0)	0.2
Liagore rubromaculata	0.002 (0.002)	0.001 (0.001)	17 (0)	0.2
Liagore sp.	0.003 (0.002)	0.002 (0.001)	14.75 (2.25)	1
Liocranium praepositum	0.646 (0.338)	0.049 (0.024)	83.43 (5.78)	1.4
Lophodiodon calori	0.036 (0.036)	0.004 (0.004)	47 (0)	0.2
Lophozozymus neoxanthops	0.018 (0.018)	0.001 (0.001)	42 (0)	0.2
Lovenia elongata	0.308 (0.235)	0.023 (0.011)	40 (7.31)	1.2
Luidia sp.	1.545 (0.586)	0.052 (0.018)	123.6 (9.59)	8.4
Lupocyclus phillippinensis	0.062 (0.062)	0.003 (0.003)	35 (0)	0.2
Lupocyclus rotundatus	2.72 (0.413)	0.426 (0.237)	33.15 (0.53)	24.6
Lutjanus malabaricus	6.888 (1.38)	0.169 (0.027)	106.93 (5.11)	15.8
Lutjanus quinquelineatus	0.006 (0.006)	0.001 (0.001)	50 (0)	0.2
Lutjanus russelli	0.576 (0.565)	0.004 (0.003)	175.5 (55.5)	0.5
Lutjanus sebae	0.363 (0.145)	0.008 (0.002)	105.78 (12.42)	3.8
Lutjanus vitta	0.666 (0.319)	0.014 (0.006)	121.24 (7.99)	2.2
Matuta granulosa	0.027 (0.019)	0.003 (0.002)	38 (1)	0.5
Matuta inermis	0.119 (0.119)	0.004 (0.004)	38 (0)	0.2
Megalaspis cordyla	0.221 (0.185)	0.034 (0.033)	119.64 (50.36)	0.5
Meiacanthus luteus	0.003 (0.003)	0.001 (0.001)	75 (0)	0.2
Melaxinia vitrea	0.129 (0.102)	0.02 (0.016)	29.89 (1.38)	1.2
Metapenaeopsis palmensis	46.006 (2.966)	20.396 (1.496)	15.47 (0.16)	97.6
Metapenaeopsis rosea	0.061 (0.043)	0.025 (0.023)	20.75 (2.25)	0.5
Metapenaeus endeavouri	2.386 (0.397)	0.273 (0.043)	19.66 (0.29)	20.8
Metapenaeus ensis	0.625 (0.26)	0.189 (0.142)	21.49 (0.45)	10.8
Metasepia pfefferi	0.428 (0.223)	0.01 (0.005)	46.25 (2.27)	1.9
Minous trachycephalus	0.01 (0.006)	0.003 (0.002)	43.33 (3.33)	0.7
Minous versicolor	0.389 (0.147)	0.027 (0.008)	62.64 (3.22)	6
Miyakea nepa	0.059 (0.059)	0.001 (0.001)	40.5 (0)	0.2
Monacanthus chinensis	1.468 (0.481)	0.135 (0.05)	69.29 (5.22)	5
Muraenesox cinereus	0.668 (0.392)	0.003 (0.002)	567.5 (66.51)	1
Nemipterus celebicus	0.063 (0.063)	0.003 (0.003)	126 (0)	0.2
Nemipterus furcosus	43.274 (9.474)	1.325 (0.354)	135.28 (1.95)	30.4
Nemipterus hexodon	101.255 (8.449)	3.329 (0.352)	116.79 (1.39)	69.1
Nemipterus mesoprion	20.822 (3.949)	1.293 (0.424)	117.1 (2.63)	15.6
Nemipterus metopias	0.742 (0.742)	0.015 (0.015)	146.25 (0)	0.2
Nemipterus nematopus	1.33 (0.39)	0.029 (0.009)	126.76 (6.29)	4.1
Nemipterus peronii	25.341 (2.222)	0.677 (0.062)	115.19 (1.76)	49.5
Nemipterus sp.	0.03 (0.03)	0.001 (0.001)	110 (0)	0.2
Nephthya sp. *1*	0.279 (0.109)	0.116 (0.05)	37.56 (2.1)	3.1
Nephthya sp. *4*	0.396 (0.242)	0.022 (0.012)	81.42 (19.53)	1
Nephthya sp. *5*	0.11 (0.066)	0.026 (0.017)	44.85 (9.05)	1
Octopus exannulatus	0.954 (0.66)	0.039 (0.012)	30 (4.39)	3.3

Species	**Mean catch rate g ha^{-1}**	**Mean catch rate n ha^{-1}**	**Mean length mm**	**Frequency of capture (%)**
Octopus graptus	0.468 (0.233)	0.005 (0.002)	64.78 (6.91)	2.2
Octopus marginatus	1.016 (0.259)	0.016 (0.005)	64.13 (5.9)	4.8
Octopus sp.	0.007 (0.007)	0.001 (0.001)	25 (0)	0.2
Odontodactylus cultrifer	0.589 (0.195)	0.012 (0.004)	37.83 (3.41)	2.9
Onigocia oligolepis	0.315 (0.315)	0.023 (0.023)	106.33 (0)	0.2
Ophiarachnella sp.	0 (0)	0.003 (0.003)	20 (0)	0.2
Ophiomyxa sp.	0.001 (0.001)	0.006 (0.006)	75.5 (0)	0.2
Ophionereis sp.	0.003 (0.002)	0.016 (0.011)	10.67 (4.67)	0.5
Ophiophsammus sp.	0.055 (0.039)	0.006 (0.004)	110.5 (0.5)	0.5
Oratosquilla anomola	0.056 (0.042)	0.007 (0.005)	21 (3)	0.5
Oratosquilla interrupta	0.491 (0.15)	0.039 (0.011)	23.02 (1.03)	4.1
Oratosquilla woodmasoni	3.844 (0.782)	0.127 (0.024)	27.9 (0.65)	15.3
Ostracion cubicus	2.3 (0.583)	0.336 (0.114)	56.12 (4.46)	9.6
Ostracion nasus	4.164 (0.985)	0.68 (0.219)	47.95 (3.3)	23.7
Oxymetopon typus	0.002 (0.002)	0.001 (0.001)	95 (0)	0.2
Oxyurichthys sp.	2.066 (0.47)	0.108 (0.026)	109.39 (2.86)	12.2
Paracentropogon longispinis	4.001 (0.814)	0.44 (0.087)	76.66 (7.05)	21.8
Parachaetodon ocellatus	1.46 (0.581)	0.097 (0.037)	74.6 (3.52)	3.3
Paramonacanthus japonicus	43.07 (7.332)	5.13 (0.879)	77.24 (0.94)	20.8
Paramonacanthus otisensis	11.401 (0.983)	0.988 (0.083)	67.63 (0.58)	56.2
Parapenaeus indicus	0.029 (0.029)	< 0.001	165 (0)	0.2
Parapenaeus longipes	0.025 (0.025)	0.009 (0.009)	21.33 (0)	0.2
Parapercis nebulosa	1.006 (0.366)	0.084 (0.021)	83.25 (7.89)	6.5
Parapercis xanthozona	0.011 (0.011)	0.003 (0.003)	71 (0)	0.2
Paraplagusia bilineata	0.555 (0.358)	0.012 (0.007)	182.83 (19.08)	0.7
Paraplagusia sinerama	0.733 (0.318)	0.007 (0.003)	250 (5.53)	2.2
Parascorpaena mossambica	0.117 (0.042)	0.012 (0.005)	74.23 (4.29)	2.4
Parthenope longimanus	0.016 (0.016)	0.002 (0.002)	26 (0)	0.2
Pecten jacobaeus	0.061 (0.061)	0.003 (0.003)	53 (0)	0.2
Pegasus volitans	0.243 (0.107)	0.059 (0.024)	109.26 (3.09)	3.1
Pelates quadrilineatus	6.212 (1.505)	0.244 (0.055)	102.07 (1.24)	14.4
Pelates sexlineatus	0.258 (0.153)	0.007 (0.004)	116.25 (6.64)	1.2
Pellona ditchela	0.455 (0.153)	0.022 (0.009)	112.13 (3.87)	2.9
Pentacta anceps	0.018 (0.018)	0.003 (0.003)	41 (0)	0.2
Pentacta sp.	0.15 (0.15)	0.01 (0.01)	43 (0)	0.2
Pentapodus aureofasciatus	0.048 (0.048)	0.003 (0.003)	111 (0)	0.2
Pentapodus paradiseus	16.654 (5.999)	0.967 (0.421)	108.06 (3.42)	11.7
Pentapodus setosus	2.085 (1.524)	0.101 (0.076)	115.62 (4.68)	0.5
Pentaprion longimanus	17.485 (3.263)	0.851 (0.128)	80.92 (1)	34.4
Peronella sp.	0.304 (0.117)	0.058 (0.017)	38.48 (4.67)	6.9
Petrarctus demani	1.982 (0.217)	0.278 (0.029)	19.78 (0.38)	30.4
Phalangipes longipes	0.001 (0.001)	0.001 (0.001)	13 (0)	0.2
Phalangipes sp.	0 (0)	0.002 (0.002)	18 (0)	0.2
Photololigo chinensis	0.502 (0.221)	0.009 (0.003)	95.02 (20.37)	2.4
Photololigo sp.	0.004 (0.004)	0.001 (0.001)	40 (0)	0.2
Placamen sp.	0.021 (0.016)	0.006 (0.004)	22.5 (3.5)	0.5
Placuna placenta	0.149 (0.149)	0.002 (0.002)	117 (0)	0.2
Platax batavianus	0.007 (0.007)	0.001 (0.001)	50 (0)	0.2
Platax teira	5.056 (1.173)	0.112 (0.021)	87 (4.01)	11.5
Platycephalus endrachtensis	0.382 (0.382)	0.001 (0.001)	340 (0)	0.2
Platycephalus indicus	0.724 (0.473)	0.005 (0.003)	270.83 (22.1)	0.7
Plotosus lineatus	13.826 (5.131)	0.613 (0.227)	151.19 (7.69)	12.9
Plumularia sp.	0.001 (0.001)	0.01 (0.006)	142.33 (32.64)	0.7
Podopthalmus vigil	4.166 (0.814)	0.132 (0.026)	72.99 (2.17)	14.8

Species	**Mean catch rate g ha^{-1}**	**Mean catch rate n ha^{-1}**	**Mean length mm**	**Frequency of capture (%)**
Polydactylus multiradiatus	4.16 (1.184)	0.075 (0.02)	122.77 (2.15)	7.2
Pomacentrus nagasakiensis	0.078 (0.071)	0.006 (0.004)	101.5 (48.5)	0.5
Pomadasys argenteus	3.54 (1.469)	0.277 (0.116)	90.73 (1.82)	3.6
Pomadasys argyreus	3.51 (1.132)	0.183 (0.066)	95.15 (2)	5
Pomadasys kaakan	0.391 (0.279)	0.005 (0.003)	168 (24.85)	0.7
Pomadasys maculatus	10.952 (3.364)	0.466 (0.203)	110.45 (2.82)	12.2
Porcellanidae sp.	0.001 (0.001)	0.005 (0.005)	3.67 (0)	0.2
Portunus aburatosubo	0.46 (0.263)	0.049 (0.027)	39.4 (1.09)	1.2
Portunus acerbiterminalis	0.104 (0.026)	0.049 (0.008)	30.89 (0.58)	10.8
Portunus argentatus	1.16 (0.467)	0.124 (0.051)	38.25 (0.53)	2.9
Portunus gladiator	0.036 (0.036)	0.003 (0.003)	40 (0)	0.2
Portunus gracilimanus	3.178 (0.436)	0.368 (0.046)	36.16 (0.39)	34.7
Portunus granulatus	0.268 (0.268)	0.022 (0.022)	41 (0)	0.2
Portunus hastatoides	35.09 (8.2)	3.651 (0.894)	42.08 (0.56)	11.2
Portunus innominatus	0.142 (0.142)	0.015 (0.015)	39 (0)	0.2
Portunus orbitosinus	0.039 (0.015)	0.024 (0.008)	30.64 (0.91)	2.9
Portunus pseudorargentatus	0.021 (0.021)	0.005 (0.005)	42 (0)	0.2
Portunus rubromarginatus	19.346 (4.461)	1.269 (0.351)	49.28 (0.56)	26.8
Portunus rugosus	0.046 (0.043)	0.027 (0.023)	23.92 (0.58)	0.5
Portunus tenuipes	71.018 (4.625)	6.969 (0.434)	41.48 (0.2)	77.3
Priacanthus tayenus	83.413 (6.106)	1.31 (0.095)	138.15 (1.41)	71.8
Pristotis jerdoni	7.352 (1.486)	0.648 (0.121)	70.23 (1.26)	18.7
Psammodiscus ocellatus	0.111 (0.073)	0.009 (0.006)	99.44 (2.94)	0.7
Psettodes erumei	30.33 (4.135)	0.212 (0.023)	214.5 (4.02)	28.7
Pseudamia amblyuropterus	0.164 (0.071)	0.024 (0.011)	83.33 (6.84)	1.4
Pseudocolochirus sp.	0.461 (0.298)	0.002 (0.001)	146 (27.01)	0.7
Pseudomonacanthus elongatus	2.105 (0.591)	0.142 (0.04)	106.08 (2.98)	4.3
Pseudomonacanthus peroni	4.289 (1.256)	0.163 (0.041)	108.31 (6.01)	10.8
Pseudorhombus argus	4.471 (1.05)	0.109 (0.024)	161.24 (3.85)	7.4
Pseudorhombus arsius	21.799 (2.566)	0.276 (0.035)	198.4 (2.14)	29.4
Pseudorhombus diplospilus	20.41 (2.925)	0.343 (0.045)	179.13 (3.1)	32.3
Pseudorhombus elevatus	7.426 (1.08)	0.4 (0.064)	119.42 (1.18)	37.3
Pseudorhombus jenynsii	3.544 (1.046)	0.051 (0.014)	184.21 (6.12)	5
Pseudorhombus spinosus	15.785 (1.957)	0.372 (0.044)	172.44 (1.87)	35.6
Pteroeides sp.	0.051 (0.025)	0.01 (0.004)	123 (9.59)	2.2
Pterois volitans	0.82 (0.285)	0.014 (0.004)	124.13 (7.23)	4.8
Quollastria gonypetes	1.88 (0.31)	0.154 (0.021)	21.44 (0.65)	21.8
Rastrelliger kanagurta	0.261 (0.159)	0.01 (0.008)	143.63 (33.63)	1
Retiflustra sp.	0.001 (0.001)	0.003 (0.003)	44 (0)	0.2
Rhynchobatus australiae	14.421 (12.036)	0.003 (0.002)	882 (104.66)	1.4
Rogadius asper	0.036 (0.036)	0.004 (0.004)	78 (0)	0.2
Samaris cristatus	0.088 (0.088)	0.007 (0.007)	101.33 (0)	0.2
Sardinella albella	1.898 (0.359)	0.103 (0.026)	114.27 (2.56)	11.7
Sardinella gibbosa	0.036 (0.026)	0.003 (0.002)	95 (5)	0.5
Saurenchelys sp.	0.133 (0.063)	0.006 (0.003)	362.33 (16.41)	1.4
Saurida grandisquamis	114.87 (6.695)	1.622 (0.08)	181.12 (1.32)	75.8
Saurida longimanus	3.422 (1.268)	0.057 (0.018)	188.88 (18.2)	2.9
Saurida micropectoralis	94.182 (7.134)	0.645 (0.05)	225.72 (2.91)	54.1
Saurida nebulosa	2.677 (1.048)	0.126 (0.035)	121.96 (11.32)	6.5
Scleractinia sp.	0.12 (0.058)	0.004 (0.003)		1.4
Scolopsis affinis	0.009 (0.009)	0.003 (0.003)	60 (0)	0.2
Scolopsis monogramma	0.228 (0.228)	0.003 (0.003)	177 (0)	0.2
Scolopsis taeniopterus	510.846 (31.105)	21.322 (1.35)	104.13 (0.89)	97.1
Scomberomorus munroi	0.438 (0.438)	0.001 (0.001)	450 (0)	0.2

Species	Mean catch rate g ha^{-1}	Mean catch rate n ha^{-1}	Mean length mm	Frequency of capture (%)
Scorpaena cardinalis	0.012 (0.012)	0.001 (0.001)	75 (0)	0.2
Scyllarus sp.	0.001 (0.001)	0.001 (0.001)	10 (0)	0.2
Scyllarus sp. *2*	3.199 (0.653)	0.338 (0.064)	25.36 (0.89)	11.2
Secutor insidiator	0.06 (0.038)	0.006 (0.003)	63.75 (9.87)	1
Secutor ruconius	0.335 (0.141)	0.058 (0.034)	67.11 (5.42)	2.6
Selar boops	1.839 (0.528)	0.066 (0.02)	137.6 (6.23)	4.8
Selaroides leptolepis	18.076 (3.273)	0.517 (0.079)	112.72 (1.71)	33.3
Sepia elliptica	6.456 (0.815)	0.243 (0.021)	51.35 (1.19)	36.8
Sepia papuensis	27.982 (4.212)	1.101 (0.17)	56.23 (1.39)	16.7
Sepia pharaonis	3.249 (0.676)	0.063 (0.009)	69.35 (3.42)	17.2
Sepia plangon	0.242 (0.125)	0.007 (0.003)	71.2 (5.03)	1.2
Sepia smithi	6.535 (0.969)	0.177 (0.023)	61 (2.49)	22.2
Sepia sp.	7.798 (2.944)	0.283 (0.087)	54.09 (3.41)	7.2
Setipinna tenufilis	0.002 (0.002)	0.003 (0.003)	31 (0)	0.2
Sicyonia cristata	0.059 (0.039)	0.027 (0.015)	13.33 (1.43)	2.2
Siganus canaliculatus	2.963 (1.244)	0.132 (0.065)	127.03 (6.69)	2.6
Siganus fuscescens	28.706 (9.561)	1.548 (0.668)	117.5 (1.59)	23.4
Sillago maculata	38.136 (7.145)	0.753 (0.144)	160.21 (1.48)	27
Sillago sihama	10.256 (1.963)	0.361 (0.074)	140.16 (1.47)	16.3
Siphamia roseigaster	0.005 (0.005)	0.001 (0.001)	50 (0)	0.2
Sirembo imberbis	0.638 (0.175)	0.025 (0.007)	152.92 (3.09)	7.2
Sorsogona tuberculata	0.233 (0.212)	0.02 (0.017)	85.33 (15.5)	0.7
Sphyraena obtusata	0.74 (0.322)	0.006 (0.002)	250 (18.9)	2.2
Sphyraena putnamae	0.069 (0.069)	< 0.001	350 (0)	0.2
Steginoporella sp.	0 (0)	0.004 (0.004)	20 (0)	0.2
Stellaster equestris	0.416 (0.219)	0.011 (0.005)	129 (11.3)	1
Stolephorus indicus	0.371 (0.302)	0.157 (0.1)	56.3 (4.96)	2.6
Stolephorus waitei	0.046 (0.024)	0.003 (0.002)	107 (14.28)	1.2
Stolephorus watei	0.025 (0.019)	0.017 (0.014)	64.4 (4.6)	0.5
Strabozebrias cancellatus	0.046 (0.046)	0.004 (0.004)	99 (0)	0.2
Strombus vittatus	0.024 (0.024)	0.003 (0.003)	56 (0)	0.2
Suggrundus macracanthus	21.769 (1.783)	1.304 (0.097)	107.12 (1.16)	66.7
Suggrundus sp.	0.552 (0.39)	0.006 (0.005)	224 (21)	0.5
Synalpheus sp.	0 (0)	0.009 (0.005)	2 (0)	0.7
Synchiropus rameus	3.092 (1.032)	0.166 (0.052)	111.8 (3.15)	6.7
Syngnathidae sp. *1*	0.015 (0.015)	0.003 (0.003)	266 (0)	0.2
Synodus hoshinonis	12.049 (1.755)	0.552 (0.082)	127.01 (1.66)	23.7
Synodus indicus	0.263 (0.244)	0.014 (0.012)	118.38 (17.38)	0.5
Synodus jaculum	0.236 (0.187)	0.006 (0.005)	152.5 (17.5)	0.5
Synodus macrops	0.426 (0.183)	0.028 (0.011)	117.06 (8.78)	1.9
Synodus sageneus	0.541 (0.248)	0.019 (0.011)	153.36 (4.66)	1.4
Synodus similis	0.083 (0.083)	0.004 (0.004)	130 (0)	0.2
Synodus sp.	0.011 (0.011)	< 0.001	130 (0)	0.2
Synodus variegatus	0.333 (0.333)	0.01 (0.01)	149.33 (0)	0.2
Tathicarpus butleri	0.264 (0.134)	0.024 (0.012)	76.6 (4.39)	1.2
Terapon jarbua	0.202 (0.093)	0.004 (0.002)	122.14 (3.43)	1.7
Terapon theraps	3.193 (0.749)	0.103 (0.02)	111.98 (2.93)	12.9
Tetrabrachium ocellatum	0.323 (0.096)	0.039 (0.01)	53.66 (1.95)	5.5
Thalamita danae	0.024 (0.024)	0.003 (0.003)	36 (0)	0.2
Thalamita pavidens	0.036 (0.036)	0.003 (0.003)	41 (0)	0.2
Thalamita sima	0.411 (0.146)	0.044 (0.014)	34.68 (0.87)	7.2
Thalamita sp.	0.026 (0.021)	0.003 (0.003)	39.5 (3.5)	0.5
Thalassodendron ciliatum	0.046 (0.046)	0.169 (0.169)	99.53 (0)	0.2
Thamnaconus striatus	0.08 (0.08)	0.004 (0.004)	107 (0)	0.2

Species	**Mean catch rate g ha^{-1}**	**Mean catch rate n ha^{-1}**	**Mean length mm**	**Frequency of capture (%)**
Thryssa hamiltonii	1.417 (0.362)	0.034 (0.01)	157.76 (4.39)	5
Thryssa setirostris	1.397 (0.422)	0.038 (0.011)	137.18 (4.59)	6.9
Torquigener hicksi	0.058 (0.058)	0.003 (0.003)	97 (0)	0.2
Torquigener pallimaculatus	9.738 (1.545)	0.539 (0.111)	92.75 (1.41)	25.6
Torquigener whitleyi	20.028 (2.165)	0.875 (0.106)	82.69 (0.84)	44
Trachinocephalus myops	0.847 (0.32)	0.027 (0.01)	145.33 (5.21)	2.9
Trachypenaeus anchoralis	27.223 (2.189)	11.197 (1.044)	16.89 (0.2)	80.4
Trachypenaeus curvirostris	0.108 (0.097)	0.06 (0.053)	18.72 (0.22)	0.5
Trachypenaeus granulosus	9.048 (0.907)	2.742 (0.309)	15.38 (0.17)	51
Trachypenaeus sp.	0.752 (0.752)	0.02 (0.02)	15.32 (0)	0.2
Tragulichthys jaculiferus	4.52 (1.1)	0.045 (0.01)	97.88 (6.11)	7.2
Triacanthus biaculeatus	0.192 (0.101)	0.013 (0.006)	94.4 (20.68)	1.2
Triacanthus nieuhofi	0.032 (0.032)	0.001 (0.001)	120 (0)	0.2
Trichiurus lepturus	0.014 (0.014)	0.001 (0.001)	315 (0)	0.2
Tripodichthys angustifrons	0.054 (0.042)	0.01 (0.008)	75.33 (5.33)	0.5
Trixiphichthys weberi	4.835 (2.405)	0.328 (0.15)	107.34 (5.11)	12.2
Ulua aurochs	0.067 (0.043)	0.01 (0.006)	68 (10.02)	0.7
Umbellifera sp. *3*	0.179 (0.179)	0.003 (0.003)	167 (0)	0.2
Unidentified Adeonellidae	0.007 (0.005)	0.007 (0.005)	53.5 (3.5)	0.5
Unidentified Alcyonarian	2.016 (0.593)	0.048 (0.032)	52.5 (0)	18.4
Unidentified Alpheidae	0.003 (0.002)	0.003 (0.002)	14 (0.71)	1
Unidentified Amphinomidae	0.001 (0.001)	0.002 (0.001)	30 (0)	0.5
Unidentified Apogon	0.075 (0.056)	0.003 (0.002)	102.5 (32.5)	0.5
Unidentified Ascidian	3.63 (0.83)	0.213 (0.037)	60.91 (3.18)	16.7
Unidentified Asteroidea	2.632 (0.875)	0.133 (0.03)	100.18 (10.55)	10.8
Unidentified Bivalve	0.169 (0.091)	0.022 (0.009)	27.15 (3.16)	2.4
Unidentified Bothidae	0.204 (0.119)	0.014 (0.008)	111 (7.37)	0.7
Unidentified Brittle Star	0.183 (0.074)	0.123 (0.051)	67.8 (7.6)	6
Unidentified Bryozoan	0.281 (0.107)	0.074 (0.02)	46.9 (3.85)	8.6
Unidentified Calappidae	0.212 (0.093)	0.019 (0.006)	34.54 (3.22)	3.3
Unidentified Carangidae	0.914 (0.354)	0.033 (0.02)	175.17 (9.2)	2.9
Unidentified Clupeidae	0.159 (0.085)	0.013 (0.008)	110 (0)	1.2
Unidentified Coelenterate	0.077 (0.076)	0.001 (0.001)	69.5 (43.5)	0.5
Unidentified Coral	0.014 (0.007)	0.003 (0.003)	160 (0)	2.2
Unidentified Crab	0.05 (0.048)	0.005 (0.004)	23 (10.61)	0.7
Unidentified Crinoid	1.97 (0.479)	0.172 (0.043)	49.54 (4.91)	13.6
Unidentified Cynoglossid	0.419 (0.212)	0.008 (0.003)	173.33 (23.2)	1.9
Unidentified Dasyatidae	0.818 (0.642)	0.008 (0.005)		0.5
Unidentified Diodontid	0.427 (0.341)	0.004 (0.003)	95 (5)	0.5
Unidentified Diogenid	0.007 (0.007)	0.001 (0.001)	14 (0)	0.2
Unidentified Dorippid	0.005 (0.005)	0.01 (0.01)	12 (0)	0.2
Unidentified Echinoidea	0.138 (0.126)	0.095 (0.057)	23.56 (3.42)	1.2
Unidentified Eel	0.116 (0.068)	0.004 (0.003)	265 (27.54)	0.7
Unidentified Eunicid	0 (0)	0.001 (0.001)	70 (0)	0.2
Unidentified Flabellifera	0.006 (0.004)	0.012 (0.007)	22.83 (2.32)	0.7
Unidentified Gastropod	0.182 (0.08)	0.026 (0.012)	42.5 (4.09)	2.2
Unidentified Glycymerididae	0.043 (0.043)	0.005 (0.005)	37 (0)	0.2
Unidentified Gobiidae	0.469 (0.235)	0.026 (0.011)	84.52 (3.04)	2.4
Unidentified Gorgonian	0.49 (0.407)	0.023 (0.013)	205.5 (55.73)	1
Unidentified Hemiramphidae	0.021 (0.011)	0.003 (0.002)	153.75 (42.2)	1
Unidentified Holothurian	7.035 (1.484)	0.196 (0.036)	92.78 (5.17)	18.9
Unidentified Hydroid	0.617 (0.215)	0.087 (0.025)	136.43 (18.89)	8.6
Unidentified Hydrozoa	0.001 (0.001)	< 0.001		0.2
Unidentified Isopoda	0.002 (0.001)	0.005 (0.004)	14.75 (4.25)	0.5

Species	**Mean catch rate g ha^{-1}**	**Mean catch rate n ha^{-1}**	**Mean length mm**	**Frequency of capture (%)**
Unidentified Leucosiidae	0.07 (0.067)	0.012 (0.01)	18.67 (2.73)	0.7
Unidentified Loliginidae	0.734 (0.344)	0.036 (0.009)	65.4 (11.4)	5.5
Unidentified Lopha	0.008 (0.008)	0.001 (0.001)	43.67 (0)	0.2
Unidentified Lumbrineridae	0.003 (0.003)	0.001 (0.001)	115 (0)	0.2
Unidentified Majidae	0.021 (0.01)	0.018 (0.007)	12.17 (0.96)	2.4
Unidentified Mugiloididae	0.008 (0.007)	0.006 (0.005)	15.67 (0)	0.5
Unidentified Muricidae	0.321 (0.321)	0.036 (0.036)	46.25 (0)	0.2
Unidentified Mytilidae	0.012 (0.012)	0.004 (0.004)	18.5 (0)	0.2
Unidentified Nudibranch	0.007 (0.005)	0.002 (0.001)	53.5 (0)	0.5
Unidentified Octopoda	0.038 (0.038)	0.003 (0.002)	34 (28)	0.5
Unidentified Ostreidae	0.362 (0.362)	0.01 (0.01)	73.33 (0)	0.2
Unidentified Parthenope	0.003 (0.003)	0.001 (0.001)	39 (0)	0.2
Unidentified Parthenopidae	0.003 (0.003)	0.003 (0.002)	24.5 (11.5)	0.5
Unidentified Pectindae	0.006 (0.004)	0.001 (0.001)		0.5
Unidentified Penaeid	0.108 (0.101)	0.003 (0.002)		0.5
Unidentified Phidoloporidae	0.002 (0.002)	0.003 (0.003)	23 (0)	0.2
Unidentified Pilumnidae	0.002 (0.002)	0.003 (0.003)	8.5 (0)	0.2
Unidentified Pinnidae	0.33 (0.33)	0.002 (0.002)	360 (0)	0.2
Unidentified Platycephalidae	1.015 (0.698)	0.005 (0.003)	275 (65.26)	0.7
Unidentified Polychaete	0.044 (0.032)	0.031 (0.021)	59.93 (12.89)	1.9
Unidentified Portunidae	0.003 (0.002)	0.002 (0.001)	27.67 (2.67)	0.7
Unidentified Raniniidae	0.042 (0.023)	0.007 (0.004)	18.17 (2.23)	1.4
Unidentified Scorpaenidae	0.289 (0.246)	0.005 (0.002)	73.33 (7.22)	1
Unidentified Sea Urchin	0.331 (0.102)	0.01 (0.003)	78.59 (3.33)	4.5
Unidentified Sillaginidae	0.564 (0.467)	0.016 (0.012)	147.63 (14.13)	0.5
Unidentified Soleidae	0.174 (0.151)	0.014 (0.013)	105.7 (9.3)	0.5
Unidentified Sponge	22.269 (6.813)	0.857 (0.326)	89.36 (10.46)	14.8
Unidentified Squillidae	0.074 (0.049)	0.005 (0.003)	23.4 (2.82)	1.2
Unidentified Strombidae	0.02 (0.02)	0.004 (0.004)	47 (0)	0.2
Unidentified Turbinaria	0.066 (0.059)	0.02 (0.013)	68.33 (42.86)	0.7
Unidentified Uranoscopidae	0.408 (0.408)	0.023 (0.022)	64.5 (39.5)	0.5
Unidentified Urochordata	0.184 (0.184)	0.006 (0.006)	76.5 (0)	0.2
Unidentified Veneridae	0.034 (0.019)	0.007 (0.004)	29 (8.02)	0.7
Unidentified Xanthidae	0.011 (0.01)	0.006 (0.004)	15 (8)	0.5
Upeneus asymmetricus	27.898 (11.421)	1.211 (0.554)	113.55 (1.19)	27
Upeneus luzonius	10.392 (6.743)	0.63 (0.426)	111.9 (2.78)	6
Upeneus moluccensis	0.809 (0.255)	0.093 (0.023)	87.43 (3.79)	8.1
Upeneus sulphureus	95.924 (9.338)	4.971 (0.497)	89.58 (0.6)	46.9
Upeneus sundaicus	118.969 (9.615)	4.182 (0.425)	114.34 (0.65)	90.4
Upeneus tragula	16.016 (2.84)	0.926 (0.175)	98.48 (1.19)	28.2
Upeneus vittatus	0.646 (0.46)	0.032 (0.029)	137.83 (9.2)	1.7
Uroconger lepturus	0.387 (0.291)	0.005 (0.004)	337.5 (32.5)	0.5
Venus lamellaris	0.003 (0.003)	0.003 (0.003)	20 (0)	0.2
Volva volva	0.011 (0.011)	0.002 (0.002)	20 (0)	0.2
Xiphasia setifer	0.024 (0.018)	0.002 (0.001)	301.67 (80.95)	0.7
Xiphocheilus typus	6.54 (0.644)	0.322 (0.033)	96.9 (1.07)	34.7
Yongeichthys sp.	1.77 (0.346)	0.167 (0.027)	74.23 (1.72)	14.8
Zabidius novaemaculatus	2.452 (0.743)	0.041 (0.013)	113.19 (5.01)	3.8
Zebrias craticulus	0.134 (0.094)	0.008 (0.005)	114.5 (8.33)	1
Zebrias quagga	0.128 (0.066)	0.006 (0.003)	118 (4.06)	1.2

Appendix 3. List of 488 taxa in the Queensland saucer scallop fishery trawl bycatch based on samples taken from 368 net trawls from the research charter and opportunistically sampling the fleet between February 2001 and November 2002. Mean catch rates are in grams and numbers per hectare, mean lengths (mm) are fork length or standard length for fish, carapace length for crustaceans, disc width or length for elasmobranchs, total length for echinoderms, and shell length for molluscs. Includes small or undersize principal target and permitted species. Frequency is percentage occurrence in 368 net trawls. Standard errors in brackets.

Species	**Mean catch rate g ha^{-1}**	**Mean catch rate n ha^{-1}**	**Mean length mm**	**Frequency of capture (%)**
Abalistes stellaris	20.73 (6.491)	0.148 (0.028)	123.96 (6.7)	11.4
Acanthogorgiidae	0.024 (0.017)	< 0.001		0.5
Acanthurus mata	0.186 (0.186)	0.003 (0.003)	120 (0)	0.3
Actaea tuberculosa	0.008 (0.005)	0.007 (0.004)	13.2 (0.8)	1.1
Actinopyga miliaris	48.574 (10.701)	0.11 (0.022)	179.55 (3.77)	13.6
Adventor elongatus	0.032 (0.026)	0.004 (0.003)	68.33 (6.01)	0.8
Agelas sp.	1.321 (0.889)	< 0.001		0.8
Aipysurus duboisii	0.147 (0.147)	< 0.001		0.3
Alepes sp.	0.386 (0.386)	0.005 (0.005)	157.5 (4.79)	0.3
Aliaporcellana suluensis	0.003 (0.002)	0.025 (0.019)	5.21 (0.26)	0.5
Alpheus sp.	0.005 (0.003)	0.007 (0.005)	7.67 (0.67)	0.8
Alutera monoceros	0.166 (0.093)	0.002 (0.002)	182.5 (41.36)	1.1
Ambiserrula jugosa	4.607 (1.114)	0.064 (0.014)	166.35 (5.33)	7.3
Amphimedon sp.	4.391 (1.478)	< 0.001		3.5
Amusium pleuronectes	0.228 (0.115)	0.013 (0.007)	61.56 (1.2)	2.7
Anacanthus barbatus	0.051 (0.037)	0.003 (0.002)	212.5 (22.5)	0.5
Anchisomus multistriatus	99.537 (17.311)	0.075 (0.013)	283.61 (10.17)	12.5
Anemone	0.064 (0.064)	0.002 (0.002)	40 (5)	0.3
Annachlamys flabellata	240.593 (46.912)	9.936 (1.921)	53.33 (0.15)	37.5
Antennarius hispidus	0.22 (0.196)	0.006 (0.005)	70 (10)	0.5
Antennarius nummifer	0.005 (0.005)	0.002 (0.002)	30 (0)	0.3
Antennarius striatus	0.681 (0.342)	0.014 (0.007)	78.13 (6.74)	1.6
Anthenea sp.	1.697 (0.428)	0.04 (0.009)	109.35 (5.99)	7.3
Apistus carinatus	4.127 (0.718)	0.125 (0.021)	100.78 (1.25)	14.7
Aplidium sp.	3.845 (1.675)	0.004 (0.004)	60 (0)	3.3
Aploactis aspera	0.114 (0.053)	0.016 (0.007)	61.67 (8.72)	1.6
Aplysia dactylomela	2.85 (1.648)	0.013 (0.005)	104.38 (15.68)	1.9
Aplysiniidae	0.136 (0.136)	< 0.001		0.3
Aplysinopsis sp.	0.073 (0.073)	< 0.001		0.3
Apogon brevicaudata	3.96 (1.21)	0.145 (0.044)	83.84 (1.58)	9.2
Apogon capricornis	0.154 (0.06)	0.019 (0.007)	63.61 (1.45)	3
Apogon cavitiensis	0.047 (0.02)	0.02 (0.008)	40.56 (3.48)	2.2
Apogon cf fuscomaculatus	0.092 (0.034)	0.015 (0.006)	53.13 (0.91)	2.2
Apogon cf semilineatus	0.016 (0.016)	0.003 (0.003)	55 (0)	0.3
Apogon ellioti	0.08 (0.033)	0.006 (0.003)	79.29 (4)	1.9
Apogon fasciatus	0.016 (0.016)	0.001 (0.001)	75 (0)	0.3
Apogon fuscomaculatus	0.458 (0.14)	0.103 (0.031)	47.6 (1.46)	6
Apogon nigripinis	1.099 (0.214)	0.118 (0.021)	54.77 (1.43)	12.2
Apogon poecilopterus	0.333 (0.233)	0.049 (0.034)	56.3 (1.05)	1.1
Apogon semilineatus	0.165 (0.062)	0.022 (0.008)	58.53 (2.42)	3
Apogon septemstriatus	0.087 (0.032)	0.032 (0.01)	42.5 (2.4)	4.3
Apogon sp.	0.089 (0.035)	0.037 (0.016)	37.5 (1.37)	2.2
Aptychotrema rostrata	75.046 (12.736)	0.114 (0.015)	559.19 (10.68)	20.1
Arca navicularis	0.04 (0.04)	0.003 (0.003)	20 (0)	0.3
Argyrops spinifer	2.846 (1.493)	0.009 (0.003)	150.91 (18.3)	2.4

Species	**Mean catch rate g ha^{-1}**	**Mean catch rate n ha^{-1}**	**Mean length mm**	**Frequency of capture (%)**
Argyrosomus sp.	20.058 (20.058)	0.001 (0.001)		0.3
Arothron manillensis	0.512 (0.512)	0.003 (0.003)	140 (0)	0.3
Arothron stellatus	22.958 (13.01)	0.009 (0.004)	212.5 (20.26)	1.6
Arotrolepis filicauda	0.333 (0.195)	0.015 (0.008)	78.85 (2.41)	1.4
Ascidian QM 320250	1.213 (1.213)	0.004 (0.004)	115 (23.63)	0.3
Asterorhombus intermedius	0.727 (0.195)	0.064 (0.018)	100.4 (3.3)	5.7
Astropecten sp.	0.498 (0.231)	0.053 (0.019)	75.87 (6.55)	5.2
Atelomycterus cf fasciatus	0.93 (0.804)	0.004 (0.003)	323.33 (67.1)	0.8
Atergatopsis inskipensis	0 (0)	0.002 (0.002)	11 (0)	0.3
Axynissa sp.	1.207 (0.761)	0.001 (0.001)		1.6
Banareia serenei	0.032 (0.032)	0.001 (0.001)	43 (0)	0.3
Barbatia velata	0.065 (0.061)	0.003 (0.002)	44 (28)	0.5
Basket Star	4.353 (1.606)	0.035 (0.009)	154.67 (19.57)	5.7
Bathypilumnus nigrispinifer	0.225 (0.131)	0.007 (0.003)	36.2 (5.96)	1.4
Bathypilumnus pugilator	0.227 (0.103)	0.032 (0.008)	19.7 (1.69)	5.4
Batrachomeus trispinosus	0.022 (0.015)	0.002 (0.002)	67.5 (7.5)	0.5
Batrachomoeus dubius	0.133 (0.068)	0.009 (0.005)	68.75 (4.27)	1.1
Bohadschia marmorata	24.133 (5.297)	0.084 (0.018)	190 (6.73)	10.9
Bolma aureola	0.219 (0.219)	0.001 (0.001)	95 (0)	0.3
Brachaluteres taylori	0.375 (0.106)	0.041 (0.011)	43.06 (2.26)	4.9
Brittle star	0.157 (0.05)	0.068 (0.02)	106.43 (10.2)	6.5
Bufonaria rana	0.089 (0.064)	0.004 (0.003)	55 (5)	0.5
Calappa philargius	0.283 (0.181)	0.002 (0.001)	98.75 (7.18)	1.1
Calliactus sp.	0.105 (0.081)	0.027 (0.021)	19.23 (1.59)	0.5
Callionymus grossi	0.1 (0.1)	0.002 (0.002)	180 (0)	0.3
Callionymus japonicus	1.02 (0.299)	0.028 (0.008)	164.41 (7.79)	4.1
Callyspongia sp.	139.698 (19.008)	< 0.001		24.2
Carangoides malabaricus	0.073 (0.062)	0.001 (0.001)	120 (6.89)	0.5
Carangoides talamparoides	0.255 (0.136)	0.003 (0.002)	126.25 (7.3)	1.4
Carinosquilla australiensis	0.145 (0.082)	0.008 (0.005)	27.25 (1.03)	1.1
Carinosquilla carinata	0.038 (0.038)	0.001 (0.001)	29 (0)	0.3
Carpilius convexus	0.001 (0.001)	< 0.001	20 (0)	0.3
Caryjoa sp.	0.005 (0.005)	< 0.001		0.3
Centriscus scutatus	0.02 (0.013)	0.004 (0.003)	152.5 (24.54)	0.8
Centrogenys vaigiensis	0.073 (0.062)	0.006 (0.004)	60 (15)	0.5
Cephalopholis boenack	0.022 (0.013)	0.007 (0.004)	48.33 (4.41)	0.8
Ceratosoma cf cornigerum	0.012 (0.012)	0.005 (0.005)	45 (0)	0.3
Chaetodermis penicilligrus	63.795 (6.634)	0.451 (0.042)	135.03 (2.22)	40.2
Chaetodon aureofasciatus	0.165 (0.165)	0.002 (0.002)	115 (0)	0.3
Chaetodontoplus duboulayi	0.544 (0.496)	0.003 (0.002)	113 (22.23)	1.1
Chaetodontoplus meredithi	6.742 (1.605)	0.065 (0.015)	116.83 (3.74)	7.1
Charybdis feriatus	8.543 (2.798)	0.019 (0.006)	131.36 (6.5)	3.5
Charybdis jaubertensis	1.383 (0.313)	0.041 (0.008)	48.52 (1.09)	7.3
Charybdis natator	14.589 (2.623)	0.078 (0.013)	91.79 (2.37)	14.9
Charybdis truncata	0.055 (0.034)	0.003 (0.002)	45.25 (2.06)	1.1
Cheilostomida	0.018 (0.018)	< 0.001		0.3
Chelmon rostratus	0.149 (0.149)	0.001 (0.001)	150 (0)	0.3
Chiloscyllium punctatum	5.771 (3.145)	0.005 (0.002)	621.8 (85.27)	1.4
Chloeia sp.	0.052 (0.052)	0.002 (0.002)	90 (0)	0.3
Choerodon cephalotes	38.884 (8.646)	0.226 (0.052)	165.57 (4.07)	14.7
Choerodon sugillatum	0.058 (0.052)	0.001 (0.001)	110 (0)	0.5
Choerodon venustus	9.497 (2.985)	0.061 (0.018)	158.65 (6.17)	4.6
Clathria sp.	0.335 (0.301)	< 0.001		0.5
Cliona sp.	2.703 (0.878)	0.004 (0.004)		3.3
Cnemidocarpa sp.	1.756 (0.493)	0.026 (0.009)	88.67 (8.04)	4.3

Species	Mean catch rate g ha^{-1}	Mean catch rate n ha^{-1}	Mean length mm	Frequency of capture (%)
Coccotropus sp.	0.088 (0.065)	0.004 (0.003)	100 (0)	0.5
Condominium sp.	0.081 (0.081)	< 0.001		0.3
Coradion altivelis	0.591 (0.253)	0.017 (0.006)	78.21 (5.34)	2.4
Coradion chrysozonus	0.434 (0.194)	0.012 (0.004)	86.25 (6.53)	2.2
Cottapistus cottoides	0.05 (0.034)	0.004 (0.002)	68.33 (13.02)	0.8
Ctenocella sp.	0.187 (0.187)	< 0.001		0.3
Culcita sp.	4.916 (3.606)	0.003 (0.003)	282.5 (12.5)	0.5
Cyclichthys orbicularis	0.346 (0.202)	0.005 (0.002)	67.86 (6.71)	1.6
Cymbacephalus nematopthalmus	0.196 (0.138)	0.002 (0.001)	230 (65)	0.5
Cynoglossus sp.	0.191 (0.097)	0.01 (0.005)	128 (4.06)	1.1
Cypselurus sp.	0.299 (0.299)	0.002 (0.002)	220 (0)	0.3
Dactyloptena macracantha	0.064 (0.045)	0.002 (0.001)	107.5 (2.5)	0.5
Dactyloptena orientalis	0.334 (0.173)	0.009 (0.005)	128.13 (12.99)	1.6
Dactyloptena papilio	1.508 (0.357)	0.044 (0.01)	97.65 (2.03)	8.2
Dactylopus dactylopus	0.207 (0.164)	0.004 (0.003)	123.33 (11.67)	0.5
Dardanus arrosor	0.026 (0.017)	0.003 (0.002)	17.67 (2.73)	0.8
Dardanus callichela	0.01 (0.01)	< 0.001	40 (0)	0.3
Dardanus crassimanus	0.006 (0.006)	0.001 (0.001)	15 (0)	0.3
Dardanus hessii	0.035 (0.025)	0.003 (0.002)	25 (0)	0.5
Dardanus imbricatus	0.015 (0.015)	0.001 (0.001)	29 (0)	0.3
Dardanus sp.	0.203 (0.137)	0.006 (0.003)	23 (2.89)	1.1
Dascyllus trimaculatus	0.71 (0.344)	0.016 (0.008)	88.89 (1.39)	1.9
Dasyatis kuhlii	44.665 (8.188)	0.062 (0.01)	277.02 (6.91)	13.6
Dasyatis leylandi	9.854 (1.766)	0.045 (0.008)	189.24 (6.67)	11.4
Decapterus russellii	0.639 (0.41)	0.008 (0.005)	167.5 (6.16)	1.1
Dendrochirus brachypterus	0.113 (0.082)	0.003 (0.002)	95 (10)	0.5
Dendrochirus zebra	0.284 (0.284)	0.005 (0.005)	115 (0)	0.3
Dendrodoris tuberculosa	0.022 (0.022)	< 0.001	90 (0)	0.3
Dendronephthya sp. *A*	1.564 (1.163)	< 0.001		1.1
Dendronephthya sp. *B*	0.038 (0.038)	< 0.001		0.3
Dendronephthya sp. *C*	0.147 (0.093)	< 0.001		0.8
Dendronephthya sp. *D*	0.557 (0.242)	< 0.001		1.9
Dendronephthya sp. *E*	0.125 (0.125)	< 0.001		0.3
Dexillichthys mulleri	0.488 (0.488)	0.001 (0.001)	260 (0)	0.3
Diagramma pictum	18.618 (7.194)	0.052 (0.015)	176.94 (12.53)	5.7
Dictyopteris sp.	0.085 (0.055)	< 0.001		1.1
Didemnidae	0.422 (0.242)	< 0.001		1.4
Diodon holocanthus	3.96 (1.653)	0.017 (0.007)	121.25 (7.43)	1.9
Diploprion bifasciatum	0.241 (0.231)	0.002 (0.002)	127.5 (17.5)	0.5
Dolabella auricularia	1.634 (0.516)	0.027 (0.007)	97.35 (8.8)	4.9
Dorippe quadridens	0.031 (0.031)	0.002 (0.002)	32 (0)	0.3
Dromia dehaani	0.134 (0.083)	0.003 (0.002)	42 (1.15)	0.8
Dromidiopsis australiensis	1.068 (0.618)	0.007 (0.004)	65.17 (9.5)	1.6
Dromidiopsis edwardsi	0.05 (0.033)	0.005 (0.003)	22.67 (4.37)	0.8
Dysidea sp.	16.89 (3.736)	0.002 (0.002)		10.3
Echinodyctium sp.	0.07 (0.07)	< 0.001		0.3
Eklonia radiata	0.182 (0.11)	< 0.001		1.9
Ellisellidae	0.018 (0.018)	< 0.001		0.3
Engyprosopon grandisquama	3.686 (0.53)	0.288 (0.042)	95.74 (1.25)	22
Engyprosopon macroptera	0.309 (0.22)	0.006 (0.004)	156.67 (6.54)	0.8
Engyprosopon sp.	0.059 (0.059)	0.001 (0.001)	160 (0)	0.3
Epinephelus coioides	4.457 (4.457)	< 0.001		0.3
Epinephelus sexfasciatus	0.042 (0.042)	0.001 (0.001)	110 (0)	0.3
Epinephelus sp	6.686 (6.686)	0.001 (0.001)		0.3
Erosa erosa	4.964 (0.925)	0.156 (0.025)	67.86 (1.9)	16

Species	**Mean catch rate g ha^{-1}**	**Mean catch rate n ha^{-1}**	**Mean length mm**	**Frequency of capture (%)**
Erugosquilla woodmasoni	0.042 (0.042)	0.001 (0.001)	33 (0)	0.3
Euprymna sp. *C*	0.023 (0.014)	0.004 (0.002)	23.33 (1.67)	0.8
Euprymna tasmanica	0.033 (0.02)	0.005 (0.003)	23.33 (4.41)	0.8
Euretaster insignis	0.701 (0.272)	0.015 (0.006)	105 (6.4)	3
Euristhmus nudiceps	0.134 (0.134)	0.001 (0.001)	275 (0)	0.3
Eurypegasus draconis	0.007 (0.007)	0.001 (0.001)	70 (0)	0.3
Fistularia commersonii	0.115 (0.115)	0.002 (0.002)	500 (0)	0.3
Fistularia petimba	0.261 (0.121)	0.007 (0.003)	404 (14.09)	1.4
Fraudella carassiops	0.043 (0.012)	0.034 (0.009)	32.25 (1.97)	4.3
Fungia sp.	0.026 (0.026)	0.003 (0.003)	35 (0)	0.3
Galathea sp.	0.011 (0.011)	0.067 (0.067)	5.78 (0.21)	0.3
Galearctus timidus	0.019 (0.019)	0.001 (0.001)	25 (0)	0.3
Gerres subfasciatus	0.029 (0.029)	< 0.001	150 (0)	0.3
Gloripallium pallium	0.049 (0.049)	0.002 (0.002)	51 (0)	0.3
Gonodactylaceus graphurus	0.162 (0.04)	0.061 (0.015)	11.86 (0.81)	6.5
Gorgonian QM 320226	0.212 (0.212)	< 0.001		0.3
Grammatobothus polyophthalmus	16.746 (2.031)	0.302 (0.036)	167.48 (1.34)	31.8
Gymnocranius audleyi	23.199 (4.776)	0.335 (0.078)	122.4 (1.94)	15.8
Gymnothorax cribroris	0.158 (0.097)	0.004 (0.003)	265 (7.64)	0.8
Gymnothorax sp.	0.233 (0.19)	0.003 (0.002)	380 (90)	0.5
Gymnothorax undulatus	0.076 (0.076)	0.001 (0.001)	325 (0)	0.3
Gymnura australis	5.351 (3.782)	0.002 (0.001)	584.67 (80.39)	0.8
Halimeda sp.	0.523 (0.223)			4.6
Halophila ovalus	0.002 (0.002)			0.3
Halophila spinulosa	31.319 (9.343)			25.3
Haplolochlaena cf maculosa	0.017 (0.017)	0.002 (0.002)	25 (0)	0.3
Harpiosquilla melanoura	0.105 (0.105)	0.001 (0.001)	46 (0)	0.3
Hemigaleus australiensis	0.444 (0.444)	0.001 (0.001)	519 (0)	0.3
Heniochus diphreutes	0.639 (0.436)	0.011 (0.007)	92.5 (5.2)	1.1
Herdmania sp.	34.05 (15.627)	0.351 (0.178)	96.46 (3.95)	8.2
Himantura sp. *A*	48.701 (47.762)	0.002 (0.001)	274 (0)	0.8
Himantura toshi	8.119 (8.119)	0.001 (0.001)	645 (0)	0.3
Himantura undulata	38.205 (38.205)	0.001 (0.001)	1330 (0)	0.3
Hippospongia elastica	0.661 (0.401)	0.001 (0.001)		0.8
Hippospongia sp.	1.274 (0.668)	0.001 (0.001)		1.4
Holothuria edulus	0.487 (0.373)	0.001 (0)	282.5 (47.5)	0.5
Holothuria fuscogliva	22.542 (8.771)	0.022 (0.008)	298.33 (7.77)	2.4
Holothuria ocellata	19.161 (3.461)	0.133 (0.023)	168.56 (3.54)	16.8
Holothurian 117	0.024 (0.024)	0.001 (0.001)	55 (0)	0.3
Holothurian 3	0.083 (0.083)	0.003 (0.003)	80 (0)	0.3
Holothurian sp.	3.106 (1.934)	0.02 (0.008)	132.78 (30.96)	2.7
Holothurian sp. *119*	0.061 (0.061)	0.001 (0.001)		0.3
Holothurian sp. *3*	0.194 (0.088)	0.006 (0.003)	80.45 (3.84)	1.6
Holothurian sp. *5*	0.046 (0.046)	0.002 (0.002)	75 (0)	0.3
Holothurian sp. *50*	0.002 (0.002)	< 0.001	50 (0)	0.3
Holothurian sp. *A*	0.003 (0.003)	< 0.001		0.3
Holothurian sp. *B*	0.018 (0.018)	0.001 (0.001)	50 (0)	0.3
Holothurian sp. *D*	4.866 (2.879)	0.005 (0.003)	266.67 (8.82)	0.8
Holothurian sp. *J*	0.839 (0.663)	0.008 (0.005)	130 (70)	0.8
Holothurian sp. *K*	0.025 (0.025)	0.003 (0.003)	45 (0)	0.3
Holothurian sp. *L*	0.76 (0.469)	0.005 (0.003)	250 (36.06)	0.8
Holothurian sp. *V*	6.924 (1.999)	0.061 (0.019)	157.32 (6.02)	5.2
Holothurian sp. *W*	0.217 (0.217)	0.001 (0.001)	105 (0)	0.3
Holothurian sp. *Y*	0.041 (0.041)	< 0.001	75 (0)	0.3
Hyastenus campbelli	0.049 (0.047)	0.004 (0.003)	21 (2.92)	0.8

Species	Mean catch rate g ha^{-1}	Mean catch rate n ha^{-1}	Mean length mm	Frequency of capture (%)
Hyastenus diacanthus	0.18 (0.105)	0.013 (0.005)	24.5 (3.64)	2.2
Hydatina albocincta	0.065 (0.065)	0.001 (0.001)	50 (0)	0.3
Hyotissa hyotis	1.937 (1.696)	0.005 (0.005)	55.33 (10.65)	0.5
Hypodistoma deerratum	1.171 (0.575)	0.003 (0.002)	142.5 (22.5)	1.6
Ianthella sp.	1.273 (1.146)	< 0.001		0.5
Ichthyscopus sannio	4.399 (1.711)	0.033 (0.009)	125.56 (7.08)	4.6
Iconaster longimanus	0.035 (0.028)	0.002 (0.002)	145 (5)	0.5
Inegocia harrisii	0.343 (0.267)	0.003 (0.002)	187.5 (27.5)	0.5
Inegocia japonica	2.149 (0.822)	0.031 (0.011)	158.46 (8.52)	2.7
Inimicus caledonicus	127.421 (16.551)	1.461 (0.191)	129.99 (1.21)	47.6
Ircinia sp.	9.255 (2.864)	0.003 (0.003)		4.6
Jonas leuteanus	0.024 (0.02)	0.002 (0.001)	31 (4.04)	0.8
Lactoria cornuta	2.254 (1.011)	0.013 (0.005)	146.88 (16.14)	1.9
Laevicardium attenuatum	0.169 (0.148)	0.004 (0.003)	60 (20)	0.5
Lagocephalus sceleratus	4.189 (3.133)	0.01 (0.004)	176.67 (31.89)	2.4
Lepidotrigla argus	5.835 (1.102)	0.222 (0.041)	98.16 (0.9)	13.6
Lepidotrigla cf japonica	1.684 (0.52)	0.067 (0.02)	100.25 (1.51)	7.6
Lepidotrigla umbrosa	0.51 (0.168)	0.021 (0.007)	97.5 (1.99)	3.5
Lethrinus genivittatus	192.083 (25.269)	2.669 (0.343)	131.77 (0.99)	47
Leucosia magna	0.017 (0.017)	0.001 (0.001)	28 (0)	0.3
Liagore rubromaculata	0.038 (0.038)	0.003 (0.003)	32 (1)	0.3
Lima lima vulgaris	0.021 (0.02)	0.004 (0.004)	23.5 (8.5)	0.5
Liocranium praepositum	0.555 (0.187)	0.026 (0.009)	80.94 (3.17)	3.5
Lisocarcinus orbicularis	0 (0)	0.001 (0.001)	10 (0)	0.3
Lissocarcinus polybioides	0 (0)	< 0.001	21 (0)	0.3
Lobophora sp.	19.819 (9.144)	< 0.001		14.9
Lophozozymus pictor	0.116 (0.116)	0.001 (0.001)	74 (0)	0.3
Lovenia sp.	0.242 (0.242)	0.006 (0.006)	60 (0)	0.3
Loxodon macrorhinus	1.433 (1.433)	0.001 (0.001)	800 (0)	0.3
Luidia maculata	2.761 (0.808)	0.021 (0.006)	271.07 (28.63)	5.4
Luidia sp.	0.014 (0.014)	0.001 (0.001)	125 (0)	0.3
Lupocyclus rotundatus	1.499 (0.604)	0.051 (0.017)	41.36 (0.85)	7.1
Lutjanus adetti	6.712 (3.03)	0.051 (0.02)	162.59 (6.6)	3.3
Lutjanus argentimaculatus	6.686 (6.686)	0.001 (0.001)		0.3
Lutjanus erythropterus	0.272 (0.272)	0.002 (0.002)	160 (0)	0.3
Lutjanus malabaricus	0.053 (0.04)	0.002 (0.001)	102 (6.44)	0.8
Lutjanus sebae	0.466 (0.231)	0.007 (0.003)	127 (3.89)	1.4
Lutjanus vittus	5.783 (2.827)	0.036 (0.015)	169.44 (11.06)	2.7
Matuta granulosa	0.279 (0.132)	0.005 (0.003)	64.11 (1.45)	1.4
Matuta inermis	0.219 (0.123)	0.009 (0.005)	34.9 (0.84)	1.4
Melaxinaea vitrea	0.004 (0.003)	0.003 (0.002)	18.5 (3.5)	0.5
Melithaeidae	0.004 (0.004)	< 0.001		0.3
Melo amphora	0.316 (0.316)	0.001 (0.001)	140 (0)	0.3
Metapenaeopsis lamellata	0.154 (0.064)	0.028 (0.011)	15.22 (1.13)	2.7
Metapenaeopsis mogiensis	0.559 (0.136)	0.093 (0.025)	17.85 (0.46)	7.6
Metapenaeopsis palmensis	0.949 (0.235)	0.163 (0.039)	17.34 (0.38)	13.6
Metapenaeopsis rosea	1.265 (0.363)	0.113 (0.03)	22.54 (0.55)	9.5
Metasepia pfefferi	0.952 (0.263)	0.029 (0.008)	42.78 (2.53)	4.6
Microcanthus strigatus	0.097 (0.069)	0.002 (0.002)	90 (10)	0.5
Microcionidae	0.596 (0.54)	< 0.001		0.5
Microcosmos sp.	0.267 (0.175)	0.007 (0.004)	37 (0)	1.1
Mimachlamys gloriosa	0.27 (0.171)	0.006 (0.004)	67.43 (3.05)	1.1
Mimachlamys senatoria	0.22 (0.119)	0.006 (0.003)	60.33 (6.5)	1.4
Minous trachycephalus	0.058 (0.032)	0.004 (0.002)	65 (2.74)	1.4
Minous versicolor	0.567 (0.196)	0.021 (0.007)	81.67 (4.04)	3.8

Species	**Mean catch rate g ha^{-1}**	**Mean catch rate n ha^{-1}**	**Mean length mm**	**Frequency of capture (%)**
Mollusc egg mass	0.823 (0.42)	0.009 (0.004)		1.9
Monacanthus chinensis	0.214 (0.121)	0.008 (0.004)	83.33 (8.72)	1.4
Nebrius ferrugineus	1.173 (1.173)	0.001 (0.001)	570 (0)	0.3
Nemipterus furcosus	0.871 (0.838)	0.002 (0.002)	205 (65)	0.5
Nemipterus peronii	0.03 (0.03)	< 0.001	170 (0)	0.3
Nemipterus theodorei	107.769 (16.513)	1.075 (0.16)	152.28 (0.85)	41
Nemocardium lyratum	0.051 (0.051)	0.001 (0.001)	56 (0)	0.3
Nephthya sp.	0.225 (0.225)	< 0.001		0.3
Nephthya sp. *1*	1.631 (0.429)	0.006 (0.004)		7.9
Nephthya sp. *2*	6.279 (3.105)	< 0.001		3.3
Nephthya sp. *3*	0.014 (0.014)	0.001 (0.001)		0.3
Nephthya sp. *4*	7.175 (1.534)	0.006 (0.003)		10.9
Nephthya sp. *5*	0.383 (0.272)	< 0.001		0.8
Nephthya sp. *6*	0.063 (0.063)	< 0.001		0.3
Niphates sp.	1.104 (1.027)	< 0.001		0.8
Niphatidae	1.637 (1.566)	< 0.001		0.5
Octopus exannulatus	1.076 (0.398)	0.027 (0.009)	36.67 (1.55)	3
Ommatocarcinus macgilvrayi	0.005 (0.005)	0.001 (0.001)	29 (0)	0.3
Onigocia macrolepis	0.228 (0.155)	0.027 (0.017)	71.54 (2.22)	2.2
Onigocia spinosa	0.06 (0.046)	0.007 (0.005)	68.33 (7.26)	0.8
Oratosquilla quinquedentata	0.009 (0.009)	< 0.001	41 (0)	0.3
Oratosquilla stephensoni	0.112 (0.082)	0.003 (0.002)	35 (5)	0.5
Ostracion nasus	11.938 (2.805)	0.058 (0.012)	154.32 (10.29)	9
Oxycheilinus bimaculatus	0.065 (0.065)	0.002 (0.002)	100 (0)	0.3
Pagrus auratus	0.784 (0.608)	0.004 (0.003)	180 (20)	0.5
Paracentropogon vespa	0.03 (0.03)	0.001 (0.001)	85 (0)	0.3
Parachaetodon ocellatus	0.047 (0.036)	0.001 (0)	88.33 (14.24)	0.8
Parahyotissa imbricata	0.03 (0.03)	0.002 (0.002)	65 (0)	0.3
Parahyotissa numisma	0.001 (0.001)	0.002 (0.002)	18 (0)	0.3
Paramonacanthus japonicus	0.055 (0.055)	0.002 (0.002)	90 (0)	0.3
Paramonacanthus lowei	22.251 (3.047)	0.529 (0.077)	103.25 (1.14)	28.8
Paramonacanthus otisensis	22.479 (2.65)	0.92 (0.106)	89.4 (0.75)	45.1
Paramonacanthus sp.	0.007 (0.007)	0.001 (0.001)	65 (0)	0.3
Parapercis clathrata	0.061 (0.061)	0.002 (0.002)	120 (0)	0.3
Parapercis nebulosa	2.379 (0.69)	0.023 (0.006)	179.67 (7.58)	4.1
Paraploactis kagoshimensis	0.263 (0.128)	0.014 (0.007)	80.71 (4.29)	1.6
Parapriacanthus ransonneti	0.077 (0.031)	0.015 (0.006)	56.88 (1.88)	2.2
Parthenope longimanus	0.03 (0.029)	0.003 (0.003)	29 (3)	0.5
Parupeneus heptacanthus	1.125 (0.462)	0.009 (0.003)	162.14 (8.85)	1.9
Pedina sp.	10.919 (3.731)	< 0.001		10.3
Pelates quadrilineatus	0.026 (0.018)	0.001 (0.001)	110 (0)	0.5
Pentaceraster sp.	101.451 (10.681)	0.797 (0.087)	157.33 (1.75)	40.8
Pentacta anceps	0.518 (0.36)	0.01 (0.004)	66.56 (11.38)	2.4
Pentapodus nagasakiensis	5.563 (1.404)	0.214 (0.054)	105.61 (1.3)	7.1
Pentapodus paradiseus	24.453 (6.063)	0.222 (0.047)	157.52 (2.91)	15.8
Peronella sp.	13.467 (2.709)	0.158 (0.028)	121.9 (2.56)	16
Petrarctus demani	1.129 (0.228)	0.066 (0.013)	27.15 (0.51)	8.7
Petroscirtes lupus	0.007 (0.007)	0.001 (0.001)	105 (0)	0.3
Phalium bandatum	0.021 (0.021)	< 0.001	90 (0)	0.3
Phallusia millari	0.629 (0.39)	0.007 (0.003)	99 (6.96)	2.2
Philine angasi	0.114 (0.095)	0.004 (0.003)	75 (25)	0.5
Phorospongidae	0.276 (0.276)	< 0.001		0.3
Photololigo sp.	1.123 (0.386)	0.015 (0.005)	118.44 (6.34)	3.3
Picrocerus armatus	0.425 (0.295)	0.016 (0.01)	34.33 (4.06)	1.6
Pilumnus hirsutus	0.006 (0.004)	0.009 (0.007)	11.33 (0.95)	0.8

Species	**Mean catch rate g ha^{-1}**	**Mean catch rate n ha^{-1}**	**Mean length mm**	**Frequency of capture (%)**
Pilumnus sp. *1*	0.025 (0.025)	0.004 (0.004)	26 (0)	0.3
Pinctada albina	0.016 (0.016)	0.001 (0.001)	48 (0)	0.3
Platax teira	1.764 (0.587)	0.02 (0.006)	102.67 (4.97)	4.1
Platycephalus arenarius	0.517 (0.276)	0.005 (0.002)	238.75 (25.2)	1.4
Platycephalus endrachtensis	0.089 (0.089)	< 0.001	375 (0)	0.3
Plotosus lineatus	0.282 (0.282)	0.006 (0.006)	186.67 (6.01)	0.3
Polycarpa sp.	46.105 (12.655)	0.457 (0.132)	93.04 (4.66)	15.5
Polychaete Tubes Empty	0.047 (0.047)	< 0.001		0.3
Polyclinidae	0.524 (0.524)	< 0.001		0.3
Portunus argentatus	0.098 (0.037)	0.017 (0.007)	36.76 (0.66)	3
Portunus gladiator	0.144 (0.144)	0.003 (0.003)	73 (0)	0.3
Portunus gracilimanus	0.049 (0.023)	0.007 (0.004)	35.95 (1.01)	1.9
Portunus haanii	0.668 (0.28)	0.026 (0.01)	58.63 (2.22)	2.7
Portunus orbitosinus	0.008 (0.008)	0.001 (0.001)	32 (0)	0.3
Portunus pelagicus	270.661 (22.169)	1.315 (0.112)	134.34 (0.64)	63.6
Portunus rubromarginatus	319.238 (37.74)	11.979 (1.581)	51.83 (0.12)	75
Portunus sanguinolentus	25.301 (5.598)	0.293 (0.065)	115.57 (0.75)	13.9
Portunus tenuipes	0.884 (0.252)	0.064 (0.018)	46.54 (0.83)	6.5
Priacanthus macracanthus	1.821 (0.689)	0.016 (0.005)	154.64 (10.45)	3.3
Priacanthus tayenus	0.498 (0.213)	0.01 (0.004)	104.83 (3.25)	1.9
Priolepis sp.	0.002 (0.002)	0.003 (0.003)	27.5 (2.5)	0.3
Prionocidaris sp.	0.116 (0.07)	0.005 (0.003)	37.33 (1.45)	0.8
Pristotis jerdoni	26.985 (4.077)	1.726 (0.256)	75.49 (0.31)	42.1
Psettodes erumei	0.042 (0.042)	< 0.001	255 (0)	0.3
Pseudochromis quinquedentatus	0.029 (0.014)	0.007 (0.003)	54.17 (5.07)	1.6
Pseudochromis sp.	0.01 (0.004)	0.005 (0.002)	36.36 (1.66)	2.2
Pseudocolochirus axiologus	1.021 (0.582)	0.004 (0.002)	122.14 (9.63)	1.4
Pseudomonacanthus elongatus	1.231 (0.62)	0.024 (0.012)	122.27 (9.78)	1.6
Pseudomonacanthus peroni	46.981 (6.621)	0.196 (0.024)	191.73 (4.31)	21.7
Pseudorhombus argus	0.362 (0.29)	0.003 (0.002)	230 (0)	0.5
Pseudorhombus arsius	0.087 (0.087)	< 0.001	260 (0)	0.3
Pseudorhombus diplospilus	5.171 (1.658)	0.024 (0.006)	271 (13.07)	4.9
Pseudorhombus dupliciocellatus	19.201 (2.815)	0.212 (0.028)	188.89 (2.49)	24.5
Pseudorhombus elevatus	1.345 (0.408)	0.043 (0.013)	138.96 (1.47)	6.8
Pseudorhombus jenynsii	5.006 (1.393)	0.028 (0.008)	240.83 (5.72)	4.6
Pseudorhombus quinquocellatus	0.535 (0.405)	0.002 (0.002)	257.5 (27.5)	0.5
Pseudorhombus spinosus	21.842 (2.613)	0.273 (0.034)	205.5 (2.25)	32.3
Pteria lata	0.013 (0.013)	0.001 (0.001)	86 (0)	0.3
Pterocaesio diagramma	0.059 (0.059)	0.002 (0.002)	125 (0)	0.3
Pteroeides sp.	0.345 (0.126)	0.018 (0.006)	81.88 (9.11)	2.7
Pterois volitans	1.179 (0.488)	0.015 (0.005)	137.73 (16.4)	3
Quollastria gonypetes	0.031 (0.031)	0.001 (0.001)	32 (0)	0.3
Ranella australasia	0.005 (0.005)	0.002 (0.002)	20 (0)	0.3
Ranina ranina	1.127 (0.738)	0.007 (0.005)	67 (2.57)	1.1
Rapana rapiformis	0.012 (0.012)	0.001 (0.001)	40 (0)	0.3
Rhinobatos typus	0.242 (0.242)	0.003 (0.003)	297.5 (17.5)	0.3
Rhynchobatus australiae	12.985 (4.502)	0.009 (0.003)	628.25 (27.56)	3.5
Rogadius patriciae	0.927 (0.356)	0.018 (0.006)	134.75 (7.3)	3.5
Samaris cristatus	0.138 (0.138)	0.004 (0.004)	160 (0)	0.3
Sand ascidian	1.084 (0.645)	< 0.001		1.4
Sarcophyton sp.	1.027 (0.725)	< 0.001		0.5
Sargassum racamosa	10.544 (4.719)			13.6
Sargassum sp.	0.134 (0.114)			0.8
Sargocentron rubrum	5.393 (2.431)	0.018 (0.008)	189 (6.57)	2.2
Saurida grandisquamis	94.835 (13.31)	0.351 (0.038)	291.34 (4.34)	34.2

Species	**Mean catch rate g ha^{-1}**	**Mean catch rate n ha^{-1}**	**Mean length mm**	**Frequency of capture (%)**
Saurida micropectoralis	1.782 (1.688)	0.002 (0.002)	325 (95)	0.5
Scaeochlamys livida	0.003 (0.002)	0.005 (0.004)	13.67 (0.88)	0.5
Scleractinia	2.274 (1.014)	< 0.001		2.2
Scolopsis monogramma	8.588 (4.27)	0.029 (0.012)	202.69 (11.35)	2.7
Scorpaena cardinalis	1.475 (0.743)	0.013 (0.006)	134.38 (8.1)	1.9
Scyllarus sp. *A*	0.004 (0.004)	0.002 (0.002)	11 (0)	0.3
Scyphozoa	3.026 (2.19)	0.005 (0.002)		1.1
Sea pen	0.323 (0.114)	0.009 (0.003)	131.56 (11.33)	3.5
Sea star	0.004 (0.004)	< 0.001	90 (0)	0.3
Sea star 10	0.202 (0.186)	0.003 (0.002)	117.5 (67.5)	0.5
Sea star 12	0.048 (0.033)	0.006 (0.004)	73.33 (9.28)	0.8
Sea star 13	0.021 (0.021)	0.001 (0.001)	90 (0)	0.3
Sea star 3	0.099 (0.045)	0.009 (0.004)	125.71 (21)	1.9
Sea star KD	0.027 (0.021)	0.002 (0.001)	122.5 (27.5)	0.5
Sea Urchin	0.179 (0.132)	0.003 (0.002)	91 (24.16)	1.1
Sea Urchin 13	0.222 (0.222)	0.002 (0.002)	70 (0)	0.3
Sea Urchin 15	0.096 (0.096)	0.001 (0.001)	80 (0)	0.3
Sea Urchin 250	0.005 (0.005)	0.001 (0.001)	25 (0)	0.3
Sea Urchin 3	50.644 (12.152)	0.488 (0.108)	66.64 (1.13)	19
Sea Urchin 6	1.645 (0.458)	0.091 (0.031)	39.84 (1.32)	7.1
Sea Urchin 84	1.9 (0.777)	0.021 (0.007)	115.67 (7.1)	2.7
Selar crumenophthalmus	0.01 (0.01)	0.001 (0.001)	70 (0)	0.3
Selaroides leptolepis	1.699 (1.16)	0.025 (0.016)	148.08 (3.74)	1.9
Sepia eliptica	0.01 (0.01)	< 0.001	60 (0)	0.3
Sepia opipara	0.9 (0.464)	0.017 (0.009)	73.93 (4)	1.4
Sepia papuensis	12.165 (1.809)	0.421 (0.058)	61.15 (0.79)	26.1
Sepia pharaonis	0.032 (0.032)	< 0.001	120 (0)	0.3
Sepia plangon	29.738 (4.183)	0.552 (0.08)	79.85 (0.96)	28.5
Sepia smithi	0.973 (0.623)	0.011 (0.007)	85.36 (3.83)	2.2
Sepia sp.	0.005 (0.005)	< 0.001	40 (0)	0.3
Sepia whitleyana	10.056 (2.459)	0.067 (0.013)	94.86 (1.98)	12
Sepioloidea lineolata	0.033 (0.021)	0.006 (0.004)	20 (0)	0.8
Serenolumnus kasijani	0.002 (0.001)	0.005 (0.004)	7.25 (0.63)	0.8
Seriolina nigrofasciata	3.539 (2.309)	0.007 (0.004)	267.5 (21.46)	1.1
Shark egg case	0.04 (0.04)	< 0.001		0.3
Sicyonia cristata	0.064 (0.038)	0.011 (0.005)	15 (1.53)	1.4
Siganus fuscescens	27.104 (4.63)	0.524 (0.101)	124.29 (1.7)	24.7
Sillago robusta	0.354 (0.215)	0.006 (0.004)	160.83 (4.36)	1.1
Solegnathus hardwickii	0.018 (0.018)	< 0.001	380 (0)	0.3
Soleichthys heterorhinos	0.491 (0.202)	0.021 (0.009)	130 (2.76)	2.2
Sorsogona tuberculata	0.34 (0.118)	0.02 (0.007)	96.11 (3.83)	3.5
Sphenopus marsupialus	0.951 (0.307)	0.032 (0.011)	56.9 (3.08)	4.1
Sphyraena flavicauda	0.511 (0.413)	0.003 (0.002)	280 (25)	0.5
Spirastrella sp.	3.964 (2.984)	< 0.001		0.5
Spondylus imperialis	0.347 (0.141)	0.023 (0.011)	38.67 (3.14)	1.9
Spondylus sp.	0.626 (0.31)	0.013 (0.005)	59.88 (5.71)	1.9
Sponge Porifera	4258.322 (503.173)	0.11 (0.008)		47
Sponge QM 320240	0.427 (0.427)			0.3
Sponge QM 320241	0.186 (0.186)			0.3
Sponge QM 320243	0.397 (0.397)			0.3
Sponge QM 320246	1.371 (1.371)			0.3
Sponge QM 320247	1.753 (1.753)			0.3
Sponge QM 320248	0.997 (0.997)			0.3
Spongia sp.	1.374 (1.28)			0.8
Stellaster equestris	4.238 (1.256)	0.109 (0.032)	111 (2.41)	9.5

Species	**Mean catch rate g ha^{-1}**	**Mean catch rate n ha^{-1}**	**Mean length mm**	**Frequency of capture (%)**
Stellaster sp.	0.13 (0.1)	0.002 (0.001)	150 (20)	0.5
Stichopus sp.	30.196 (6.752)	0.139 (0.021)	227.1 (8.89)	19.8
Styela sp.	0.009 (0.009)	0.001 (0.001)	35 (0)	0.3
Stylocheilus longicauda	0.037 (0.037)	0.003 (0.003)	57.5 (2.5)	0.3
Subergorgia sp.	0.022 (0.022)	< 0.001		0.3
Suezichthys gracilis	0.088 (0.044)	0.016 (0.008)	67 (4.06)	1.1
Suggrundus japonicus	1.915 (1.039)	0.026 (0.014)	161.67 (7.55)	1.4
Suggrundus macracanthus	0.018 (0.016)	0.001 (0.001)	90 (25)	0.5
Synalpheus stimpsoni	0.001 (0.001)	0.002 (0.002)	8 (0)	0.3
Synchiropus rameus	0.158 (0.084)	0.008 (0.004)	106.25 (17.49)	1.1
Synodus hoshinonis	0.421 (0.19)	0.014 (0.006)	134.29 (9.41)	1.9
Synodus sageneus	0.481 (0.336)	0.008 (0.005)	155 (50.58)	0.8
Synodus variegatus	0.12 (0.12)	0.001 (0.001)	170 (0)	0.3
Tamaria sp.	0.116 (0.082)	0.005 (0.003)	106.67 (18.56)	0.8
Tathicarpus butleri	0.325 (0.14)	0.015 (0.006)	65 (4.72)	1.9
Tetrosomus concatenatus	2.077 (0.889)	0.023 (0.006)	109.17 (12.65)	4.9
Thalamita intermedia	0.128 (0.071)	0.012 (0.006)	33.83 (2.02)	1.6
Thalamita sima	3.381 (1.336)	0.228 (0.084)	39.95 (0.72)	6
Thalamita sp. *A*	0.095 (0.076)	0.006 (0.005)	39.75 (2.06)	0.8
Thenus indicus	0.279 (0.109)	0.007 (0.003)	43 (2.47)	2.4
Thenus orientalis	14.045 (3.171)	0.059 (0.012)	69.02 (2.92)	9.2
Thorectandra sp.	0.106 (0.106)	< 0.001		0.3
Thysanophrys chiltonae	0.014 (0.014)	0.001 (0.001)	135 (0)	0.3
Tonna tetracotula	0.092 (0.092)	0.001 (0.001)	80 (0)	0.3
Torquigener pallimaculatus	20.041 (2.149)	0.565 (0.064)	91.87 (1.13)	35.6
Torquigener perlevis	4.178 (1.108)	0.044 (0.011)	128 (3.94)	5.7
Trachinocephalus myops	10.269 (1.975)	0.085 (0.015)	182.01 (3.79)	12.2
Trachypenaeus anchoralis	0.047 (0.047)	0.011 (0.011)	14.33 (0.33)	0.3
Trachypenaeus curvirostris	0.475 (0.103)	0.054 (0.011)	20.64 (0.6)	8.2
Trachypenaeus granulosus	0.004 (0.004)	0.001 (0.001)	21 (0)	0.3
Tragulichthys jaculiferus	8.568 (2.676)	0.031 (0.009)	130.68 (11.92)	5.4
Trixiphichthys weberi	4.533 (0.907)	0.087 (0.017)	139.34 (2)	11.1
Tudivasum armigera	0.194 (0.194)	0.002 (0.002)	80 (0)	0.3
Udotea sp.	0.466 (0.15)	< 0.001		5.7
Umbellifera sp.	1.712 (1.491)	< 0.001		0.8
Umbellifera sp. *1*	0.736 (0.417)	< 0.001		1.6
Umbellifera sp. *2*	1.09 (0.715)	< 0.001		1.1
Umbellifera sp. *3*	0.103 (0.062)	< 0.001		0.8
Unidentified Alcyonarian	1.89 (0.749)	0.004 (0.002)		3
Unidentified Ascidian	4.099 (1.589)	0.038 (0.011)	113.75 (12.16)	5.4
Unidentified Bivalve	0.619 (0.226)	0.02 (0.007)	61.94 (9.03)	3.5
Unidentified Bryozoan	41.956 (17.302)	0.007 (0.003)		16.8
Unidentified Crinoid	3.174 (0.629)	0.108 (0.02)	107.14 (12.72)	17.7
Unidentified Gorgonian	1.659 (0.621)	0.002 (0.001)	220 (0)	6
Unidentified Hydroid	0.296 (0.1)	< 0.001		5.4
Unidentified Nudibranch	0.33 (0.172)	0.005 (0.002)	102.22 (4.18)	1.6
Unidentified shell 1	15.282 (11.309)	0.002 (0.001)		0.5
Unidentified Sponge	13.06 (3.419)		60 (0)	11.7
Unidentified Stomatopod	0 (0)	< 0.001	6 (0)	0.3
Upeneus asymmetricus	8.065 (1.352)	0.225 (0.037)	115.82 (1.06)	18.5
Upeneus luzonius	10.822 (3.484)	0.14 (0.046)	144.8 (2.77)	6.3
Upeneus tragula	0.942 (0.32)	0.034 (0.01)	104.04 (3.22)	4.9
Uranoscopus terraereginae	0.649 (0.266)	0.01 (0.004)	113.46 (10.85)	3
Virgularia sp.	0.011 (0.011)	0.001 (0.001)	95 (0)	0.3
Volachlamys singaporina	0.029 (0.029)	0.001 (0.001)	52 (0)	0.3

Species	**Mean catch rate g ha^{-1}**	**Mean catch rate n ha^{-1}**	**Mean length mm**	**Frequency of capture (%)**
Xanthid sp.	0.002 (0.002)	0.002 (0.001)	11.33 (3.38)	0.5
Xenophora indica	0.045 (0.041)	0.001 (0.001)	72.5 (2.5)	0.5
Xyrichthys jacksonensis	0.55 (0.282)	0.005 (0.002)	168.33 (4.59)	1.1

Appendix 4. List of 186 species and their total weight recorded in the bycatch of 96 (48 sites x 2 nets) one-nautical trawls in southern Hervey Bay in June 2002. Includes small or undersized principal target and permitted species.

Species	Total weight (kg)
Lethrinus genivittatus	376.5768
Siganus fuscescens	109.0536
Upeneus luzonius	95.4506
Upeneus asymmetricus	78.9423
Portunus pelagicus	60.4931
Saurida grandisquamis	52.6101
Pentapodus paradiseus	38.1883
Choerodon cephalotes	23.6116
Unidentified sponge	17.9944
Paramonacanthus otisensis	16.3928
Portunus rubromarginatus	10.4946
Amusium balloti	9.264
Annachlamys flabellata	7.8094
Pelates sexlineatus	6.4391
Synodus sageneus	6.2046
Pelates quadrilineatus	5.8537
Metapenaeopsis palmensis	5.7429
Pseudorhombus arsius	5.1145
Psammoperca waigiensis	4.1196
Selaroides leptolepis	3.8446
Torquigener pallimaculatus	3.8177
Gerres subfasciatus	3.6975
Inegocia japonica	2.966
Arnoglossus intermedius	2.9014
Parapercis nebulosa	2.7883
Pseudomonacanthus peroni	2.7215
Anchisomus multistriatus	2.337
Pristotis jerdoni	2.0308
Engyprosopon grandisquama	2.0201
Sphyraena flavicauda	1.9719
Torquigener perlevis	1.9027
Nemipterus theodorei	1.8763
Pseudorhombus jenynsii	1.8673
Pomadasys maculatum	1.8094
Pseudorhombus argus	1.7131
Callyspongia sp.	1.6327
Platycephalus endrachtensis	1.6121
Halophila spinulosa	1.6037
Sillago maculata	1.4776
Torquigener whitleyi	1.4272
Portunus tenuipes	1.1998
Sea urchin 3 (CSIRO)	1.1142
Apogon fasciatus	1.1033
Inimicus caledonicus	1.0461
Chiloscyllium punctatum	1.0422
Seriolina nigrofasciata	1.0059
Pentaceraster sp	0.9815
Apogon brevicaudatus	0.9357
Alepes sp	0.9256
Platycephalus indicus	0.8518
Cymbacephalus nematophthalmus	0.8498
Thenus indicus	0.8447
Pagrus auratus	0.8161
Sepia whitleyana	0.7885
Priacanthus macracanthus	0.783
Callionymus grossi	0.7804
Pseudorhombus spinosis	0.7328
Caulerpa sertularioides	0.6933
Nemipterus peronii	0.6515
Monacanthus chinensis	0.6076
Rubble Shell	0.6024
Sepia papuensis	0.5872
Platax teira	0.5346
Trachinocephalus myops	0.4985
Lagocephalus sceleratus	0.4878
Volutidae	0.4744
Priacanthus tayenus	0.4685
Decapterus russellii	0.4545
Scolopsis taeniopterus	0.4506
Belosquilla laevis	0.4069
Dactylopus dactylopus	0.4012
Halimeda discoidea	0.3694
Holothurian sp.	0.3639
Stellaster equestris	0.3521
Charybdis natator	0.3483
Atule mate	0.3467
Holothuria ocellata	0.3379
Upeneus tragula	0.2718
Sillago robusta	0.2672
Alepes sp.	0.2599
Carangoides malabaricus	0.259
Herdmania sp.	0.2475
Apistus carinatus	0.22
Euprymna sp	0.2189
Ascidian sp.	0.2038
Platycephalus arenarius	0.199
Chaetoderma penicilligera	0.1985
Niphates sp.	0.1958
Remora remora	0.1946
Lutjanus carponotatus	0.1898
Sepia smithi	0.1871
Carangoides hedlandensis	0.1765
Diagramma pictum	0.1755
Basket Star	0.1714
Scyllarus demani	0.1672
Razor Shell;Razor Clam	0.1644
Muraenesox cinereus	0.1616
Apogon ellioti	0.1577
Scorpaenid sp	0.1541
Metapenaeus endeavouri	0.1534
Lethrinus sp	0.1507
Herklotsichthys lippa	0.1503
Ablennes hians	0.139
Centrogenys vaigiensis	0.1354
Dactyloptena orientalis	0.1353
Sepia plangon	0.1153
Urchin sp	0.1139
Apogon fuscomaculata	0.1116

Species	Total weight (kg)
Oyster	0.1047
Carangoides humerosus	0.1042
Anacanthus barbatus	0.0979
Apogon cf semilineatus	0.0958
Sea pen	0.0958
Carangoides chrysophrys	0.0948
Suggrundus harrisi	0.0896
Udotea sp	0.0829
Gnathanodon speciosus	0.0789
Suggrundus jugosus	0.0762
Dicotylichthys punctulatus	0.0752
Apogon cavitiensis	0.0746
Penaeus esculentus	0.0708
Leiognathus moretoniensis	0.0697
Holothuria notabilis	0.0668
Pseudorhombus diplospilus	0.064
Penaeus plebejus	0.0577
Lactoria cornutus	0.0512
Zebrias craticula	0.0507
Sea urchin 6 (csiro)	0.0476
Plotosus lineatus	0.0471
Parachaetodon ocellatus	0.0447
Callionymus sublaevis	0.0418
Lepidotrigla argus	0.04
Penaeus latisulcatus	0.0396
Stomatopod Mantis Shrimp	0.0385
Aploactis aspersa	0.0383
Philine sp	0.0365
Portunus rugosus	0.0361
Trachypenaeus granulosus	0.036
Callionymus limiceps	0.0348
Lepidotrigla umbrosa	0.031
Petroscirtes lupus	0.029
Sorsogoma tuberculata	0.0283
Charybdis truncata	0.025
Halamida sp	0.0239
Terapon puta	0.0232
Bivalve	0.0202
Sand Dollar	0.02
Octopus sp	0.019
Thalamita sima	0.0184
Crinoid sp.	0.0176
Soft coral	0.0168
Sillago ingennua	0.0167
Photololigo sp	0.0156
Luidia maculata	0.0155
Apogon nigripinnis	0.0149
Pseudorhombus dupliciocellatus	0.0135
Cynoglossus sp	0.0131
Gastropod	0.013
Adventor elongatus	0.0117
Penaeidae	0.0109
Callionymus japonicus	0.01
Gastropod sp.	0.0091
Sand ascidian	0.0089
Halimeda sp.	0.0089
Parapriacanthus ransonneti	0.0086
Rhynchostracion nasus	0.0086
Sepia sp	0.0079
Brachaluteres taylori	0.0076
Metapenaeus ensis	0.0071
Trachypenaeus curvirostris	0.0068
Seuzichtys devisi	0.0064
Metasepia pfefferi	0.0061
Astropecten sp	0.006
Siphamia cuniceps	0.0058
Portunus sp	0.005
Brittle Star	0.0039
Green algae	0.0032
Coral	0.0031
Hermit Crab	0.003
Hydroid	0.0029
Scyllarus sp. *A*	0.0024
Centriscus scutatus	0.0011
Scyllarus sp.	0.0011
Siphamia sp.	0.0011
Pseudochromis quinquedentatus	0.0011
Mantis shrimp sp	0.0003

Appendix 5. List of 346 taxa in the bycatch of the deepwater (> 91 m) eastern king prawn fishery based on bycatch sub-samples from 201 individual net trawls from the research charter and opportunistically sampling the fleet between March 2001 and July 2002. Mean catch rates are in grams and numbers per hectare, mean lengths (mm) are fork length or standard length for fish, carapace length for crustaceans, disc width or length for elasmobranchs, total length for echinoderms, and shell length for molluscs. Includes small or undersized principal target and permitted species. Frequency is percentage of occurrence in the 201 net trawls. Standard error in brackets.

Species	Mean catch rate g ha^{-1}	Mean catch rate n ha^{-1}	Mean length mm	Frequency of capture (%)
Amoria molleri	0.167 (0.08)	0.006 (0.003)	72.5 (0.73)	2.5
Amphichaetodon howensis	0.3 (0.3)	0.003 (0.003)	115 (0)	0.5
Amusium balloti	0.066 (0.043)	0.004 (0.002)	50.8 (1.6)	2.5
Anguilla reinhardtii	0.167 (0.167)	0.001 (0.001)	500 (0)	0.5
Anoplocapros inermis	2.879 (0.915)	0.011 (0.003)	172.32 (1.63)	7.0
Antennarius hispidus	0.002 (0.001)	0.001 (0)	30 (0.35)	1.5
Antennarius striatus	0.702 (0.253)	0.017 (0.004)	60.88 (1.8)	9.5
Antigonia rhomboidea	1.269 (0.213)	0.247 (0.038)	39.9 (0.46)	47.0
Apogon semilineatus	0.02 (0.014)	0.003 (0.002)	72.5 (1.75)	1.0
Apogonops anomalus	89.504 (34.549)	5.468 (2.158)	92.13 (0.93)	22.5
Aptychotrema rostrata	3.026 (1.622)	0.003 (0.001)	667.5 (6.17)	2.0
Arcania foliolata	0.059 (0.014)	0.017 (0.004)	20.86 (0.19)	11.0
Ariomma luridum	1.555 (0.423)	0.026 (0.007)	133.15 (1.5)	9.0
Ariosoma shiroanago	0.165 (0.117)	0.002 (0.001)	380 (0.5)	1.0
Arnoglossus sp.	0.025 (0.022)	0.011 (0.009)	64.5 (0.3)	2.0
Arnoglossus waitei	0.061 (0.036)	0.009 (0.004)	79.06 (2.62)	4.0
Arothron firmamentum	4.173 (2.69)	0.004 (0.003)	251.11 (2.52)	1.5
Aseraggodes cyaneus	0.011 (0.011)	0.001 (0.001)	100 (0)	0.5
Aseraggodes kaianus	0.062 (0.03)	0.005 (0.002)	90 (1.25)	2.5
Aseraggodes sp.	0.009 (0.009)	0.001 (0.001)	90 (0)	0.5
Astele bularra	0.154 (0.144)	0.02 (0.018)	23.4 (0.3)	2.5
Astropecten sp.	0.832 (0.325)	0.031 (0.008)	115.82 (4.02)	12.5
Asymbolus analis	0.93 (0.359)	0.005 (0.002)	375.57 (6.62)	3.5
Asymbolus rubiginosus	4.756 (1.558)	0.015 (0.005)	448.98 (1.63)	6.0
Ateleopus sp.	0.017 (0.012)	0.002 (0.002)	265 (1)	1.0
Aulopus curtirostris	7.915 (1.458)	0.631 (0.106)	89.53 (0.94)	50.5
Aulotrachichthys sp.	3.051 (0.458)	0.563 (0.085)	55.11 (0.48)	55.0
Basket star	0.022 (0.018)	0.002 (0.001)		1.0
Bathypilumnus pugilator	0 (0)	< 0.001	16 (0)	0.5
Batrachomoeus dubius	0.05 (0.05)	0.005 (0.005)	63.33 (0)	0.5
Bembras macrolepis	0.013 (0.007)	0.002 (0.001)	80.25 (1.94)	2.5
Bothidae A	0.004 (0.004)	0.001 (0.001)	85 (0)	0.5
Bothidae B	0.011 (0.011)	0.001 (0.001)	125 (0)	0.5
Brachionichthys sp.	0.022 (0.018)	0.005 (0.004)	45 (0.5)	1.0
Branchiostegus wardi	0.904 (0.562)	0.006 (0.003)	181.5 (5.42)	2.5
Brittle star	0.007 (0.005)	0.005 (0.003)	76.25 (4.38)	2.0
Caelorinchus mirus	0.075 (0.075)	0.002 (0.002)	207.5 (0)	0.5
Calappa lophos	0.246 (0.111)	0.003 (0.001)	82.03 (2.75)	3.0
Calliactus sp.	3.819 (0.433)	0.451 (0.039)	31.78 (0.77)	65.5
Callionymus draconis	0.893 (0.308)	0.064 (0.022)	94.04 (0.8)	5.0
Callionymus japonicus	0.005 (0.005)	0.001 (0.001)	75 (0)	0.5
Callionymus margaretae	0.079 (0.062)	0.007 (0.006)	105.63 (2.44)	1.0
Callionymus moretonensis	37.645 (5.48)	2.801 (0.406)	104.1 (1.42)	64.5
Canthigaster callisterna	0.168 (0.106)	0.009 (0.005)	76 (0.91)	2.5

Species	**Mean catch rate g ha^{-1}**	**Mean catch rate n ha^{-1}**	**Mean length mm**	**Frequency of capture (%)**
Carangoides equula	26.011 (13.944)	0.385 (0.184)	116.24 (1.83)	42.0
Carid sp.	0.009 (0.005)	0.005 (0.003)	11.5 (0.14)	2.0
Cassis nana	0.001 (0.001)	< 0.001	30 (0)	0.5
Centroberyx affinis	0.033 (0.033)	< 0.001	170 (0)	0.5
Cepola schlegelii	0.017 (0.017)	0.002 (0.002)	227.5 (0)	0.5
Chaetodiadema granulatum	0.002 (0.002)	< 0.001	45 (0)	0.5
Champsodon nudivittis	0.623 (0.223)	0.107 (0.04)	69.12 (0.83)	21.5
Charybdis bimaculata	35.904 (7.648)	3.18 (0.642)	36.74 (0.23)	75.5
Charybdis miles	20.76 (6.157)	0.362 (0.106)	58.54 (0.76)	23.0
Chaunax fimbriatus	0.048 (0.048)	0.001 (0.001)	95 (0)	0.5
Chelidonichthys kumu	14.675 (1.769)	0.115 (0.014)	188.58 (1)	41.0
Chelidoperca sp.	0.023 (0.016)	0.006 (0.004)	54.17 (0.42)	1.0
Chicoreus damicornis	0.007 (0.003)	0.005 (0.002)	26.67 (0.37)	3.0
Chicoreus longicornis	0.002 (0.002)	0.001 (0.001)	32.5 (0.25)	1.0
Chloeia sp.	0.167 (0.037)	0.027 (0.005)	48.21 (0.8)	14.0
Chromis abyssicola	0.279 (0.186)	0.014 (0.009)	75.6 (1.08)	3.5
Cirrhitichthys aprinus	0.056 (0.056)	0.002 (0.002)	85 (0)	0.5
Cleidopus gloriamaris	0.108 (0.077)	0.001 (0)	127.5 (0.25)	1.0
Columbarium spinicinctum	0.002 (0.002)	0.001 (0.001)	52.5 (0.75)	1.0
Conger sp.	0.005 (0.005)	0.001 (0.001)	250 (0)	0.5
Conger wilsoni	0.258 (0.258)	0.003 (0.003)	470 (0)	0.5
Crangonid sp.	0.002 (0.002)	0.003 (0.003)	11 (0)	0.5
Cryptolutea sp.	0.002 (0.002)	0.001 (0.001)	17 (0)	0.5
Cubiceps whiteleggii	0.193 (0.193)	0.003 (0.003)	141.67 (0)	0.5
Cyclichthys spilostylus	0.205 (0.205)	< 0.001	200 (0)	0.5
Cymbiola irvinae	0.064 (0.064)	0.001 (0.001)	126 (0)	0.5
Cymbiola magnifica	2.426 (1.37)	0.004 (0.002)	201.07 (3.16)	3.5
Cymbiolacca pulchra	0.003 (0.003)	< 0.001	48 (0)	0.5
Cymbiolista hunteri	0.994 (0.284)	0.008 (0.002)	121.43 (0.79)	8.5
Cynoglossus sp.	0.664 (0.26)	0.036 (0.013)	101.31 (0.67)	6.0
Dactyloptena orientalis	0.148 (0.105)	0.001 (0.001)	132.5 (8.25)	1.0
Dactyloptena papilio	5.011 (1.022)	0.131 (0.026)	107.5 (1.02)	32.0
Dardanus arrosor	7.567 (0.931)	0.226 (0.021)	25.78 (0.89)	64.0
Dardanus imbricatus	0.018 (0.016)	0.001 (0.001)	26.5 (1.15)	1.0
Dardanus sp.	0.155 (0.069)	0.008 (0.003)	24.65 (0.48)	5.0
Dasyatis thetidis	31.79 (24.117)	0.003 (0.002)	420 (1.225)	2.0
Decapterus russellii	0.051 (0.051)	< 0.001	235 (0)	0.5
Dendrochirus brachypterus	0.114 (0.063)	0.009 (0.005)	72.5 (0.35)	2.0
Dendrochirus zebra	0.277 (0.094)	0.019 (0.006)	76.67 (0.54)	6.5
Dendrodoris tuberculosa	1.185 (0.367)	0.019 (0.007)	105.91 (2.56)	6.5
Dentex spariformis	38.361 (10.284)	1.483 (0.545)	75.74 (1.67)	34.5
Diaphus watasei	0.059 (0.056)	0.01 (0.009)	62.81 (0.78)	1.0
Dicotylichthys punctulatus	0.115 (0.115)	< 0.001	230 (0)	0.5
Dipturus polyommata	4.379 (1.169)	0.031 (0.006)	206.34 (8.24)	13.5
Distorsio reticulata	0.084 (0.084)	0.006 (0.006)	53.5 (0)	0.5
Dyosomma sp.	0.179 (0.179)	0.001 (0.001)	535 (0)	0.5
Echelus sp.	0.01 (0.01)	0.001 (0.001)	280 (0)	0.5
Eklonia radiata	2.171 (0.588)	< 0.001		21.0
Eledone palari	0.112 (0.062)	0.002 (0.001)	45 (0.41)	2.0
Emmelichthys strusakeri	0.037 (0.021)	0.003 (0.001)	90 (0.96)	2.0
Engyprosopon grandisquama	0.025 (0.019)	0.002 (0.002)	100.83 (1.08)	1.0
Engyprosopon sp.	0.082 (0.079)	0.007 (0.007)	103.13 (0.31)	1.0
Entomonyx depressus	0.04 (0.021)	0.005 (0.003)	27.2 (0.14)	2.5
Epigodromia areolata	0.001 (0.001)	< 0.001	20 (0.5)	1.0
Epinephelus morrhua	0.087 (0.067)	0.004 (0.003)	105 (0)	1.0

Species	Mean catch rate g ha^{-1}	Mean catch rate n ha^{-1}	Mean length mm	Frequency of capture (%)
Epinephelus octofasciatus	0.407 (0.265)	0.004 (0.002)	136.88 (3.92)	2.0
Eplumula australiensis	0 (0)	0.001 (0.001)	6.17 (0.08)	1.0
Ericusa serricata	0.002 (0.001)	< 0.001	47.5 (0.25)	1.0
Erisphex aniarus	0.23 (0.075)	0.043 (0.009)	50.21 (0.87)	20.0
Erosa erosa	0.01 (0.01)	0.001 (0.001)	45 (0)	0.5
Etrumeus teres	0.061 (0.061)	0.001 (0.001)	181.25 (0)	0.5
Eumedonus vicinus	0.001 (0.001)	0.001 (0.001)	11.5 (0)	0.5
Euprymna sp. *B*	0.005 (0.002)	0.002 (0.001)	16 (0.37)	2.5
Euprymna sp. *C*	0.015 (0.007)	0.005 (0.002)	17 (0.19)	2.5
Euprymna tasmanica	2.002 (0.604)	0.485 (0.15)	18.41 (0.24)	37.5
Fistularia petimba	1.337 (0.36)	0.016 (0.004)	536.94 (5.36)	9.0
Foetorepus calauropomus	0.018 (0.014)	0.001 (0.001)	95 (0)	1.0
Fungia sp.	0.044 (0.017)	0.006 (0.002)	29.5 (0.91)	4.5
Galearctus timidus	0.163 (0.057)	0.033 (0.008)	16.21 (0.29)	17.0
Galeus boardmani	2.935 (0.826)	0.012 (0.003)	438.8 (1.66)	8.0
Glaucosoma scapulare	5.929 (1.386)	0.023 (0.005)	187.81 (2.48)	12.0
Glossanodon australis	0.905 (0.247)	0.156 (0.038)	80.14 (1.01)	21.5
Gnathophis grahamii	2.575 (0.473)	0.069 (0.011)	272.76 (3.19)	26.0
Goniistius vestitus	0.285 (0.229)	0.001 (0.001)	212.5 (0.25)	1.0
Gonorynchus greyi	9.169 (1.457)	0.092 (0.015)	234.99 (3.13)	29.0
Grammatobothus polyophthalmus	0.149 (0.106)	0.002 (0.002)	180 (0)	1.0
Halieutea stellata	2.854 (0.564)	0.163 (0.027)	59.07 (1.93)	43.0
Haliporoides sp.	0.002 (0.002)	0.001 (0.001)	9.6 (0)	0.5
Harpiosquilla melanoura	0.029 (0.029)	0.002 (0.002)	26 (0)	0.5
Harpiosquilla sinensis	0.274 (0.153)	0.006 (0.003)	39.75 (0.61)	2.0
Haustellum tweedianum	0.012 (0.012)	0.001 (0.001)	70 (0)	0.5
Heterodontus sp.	1.074 (0.765)	< 0.001		1.0
Heteroscyllium colcloughi	0.192 (0.192)	< 0.001	540 (0)	0.5
Holothuria ocellata	0.136 (0.136)	0.001 (0.001)	235 (0)	0.5
Holothurian sp.	0.177 (0.177)	0.001 (0.001)	285 (0)	0.5
Holothurian sp. *5*	0.157 (0.157)	0.001 (0.001)	250 (0)	0.5
Homola orientalis	0.033 (0.016)	0.005 (0.002)	16.43 (0.24)	3.5
Hoplichthys citrinus	3.525 (1.562)	0.3 (0.12)	116.16 (1.76)	8.5
Hyastenus diacanthus	0.001 (0.001)	< 0.001	29 (0)	0.5
Hydrolagus lemures	2.208 (1.733)	0.001 (0.001)	722.5 (7.25)	1.0
Hypnos monopterygius	1.003 (0.554)	0.002 (0.001)	212.5 (8.75)	2.0
Ibacus brucei	0.51 (0.123)	0.055 (0.019)	29.41 (0.37)	15.5
Ibacus chacei	3.075 (0.583)	0.212 (0.026)	24.41 (0.56)	44.5
Ibacus sp.	0.011 (0.011)	0.001 (0.001)		0.5
Ircinia sp.	0.125 (0.125)	< 0.001		0.5
Ixoides cornutus	0.119 (0.044)	0.008 (0.003)	62 (0.53)	4.5
Jonas leuteanus	0.012 (0.012)	0.001 (0.001)	45 (0)	0.5
Kempina mikado	9.42 (1.221)	0.233 (0.03)	36.33 (0.38)	44.0
Lagocephalus inermis	6.869 (1.694)	0.052 (0.014)	154.31 (3.74)	15.5
Lagocephalus spadiceus	2.647 (0.852)	0.01 (0.003)	207.5 (4.69)	7.0
Lamellaria australis	0.008 (0.008)	0.001 (0.001)	35 (0)	0.5
Latreillopsis daviei	0.003 (0.003)	0.001 (0.001)	13 (0)	0.5
Lepidoperca caesiopercula	0.349 (0.181)	0.01 (0.005)	97.1 (0.71)	2.5
Lepidotrigla argus	103.515 (9.558)	7.007 (0.874)	94.64 (1.28)	90.5
Lepidotrigla cf japonica	0.72 (0.181)	0.054 (0.016)	84.43 (1.34)	11.5
Lepidotrigla grandis	4.321 (0.991)	0.174 (0.038)	91.4 (1.89)	27.0
Leptomithrax weitei	22.945 (4.629)	0.115 (0.025)	87.63 (1.73)	35.0
Leucosia ocellata	0.056 (0.035)	0.006 (0.003)	23.64 (0.23)	3.5
Leucosyrinx queenslandica	0.003 (0.003)	0.001 (0.001)	50 (0)	0.5

Species	**Mean catch rate g ha^{-1}**	**Mean catch rate n ha^{-1}**	**Mean length mm**	**Frequency of capture (%)**
Liocarcinus corrugatus	0.011 (0.006)	0.001 (0)	33.3 (0.33)	2.5
Lophiomus setigerus	5.493 (0.761)	0.07 (0.009)	123.4 (1.33)	33.5
Luidia sp.	0.004 (0.004)	0.001 (0.001)	100 (0)	0.5
Lumiconger arafura	0.087 (0.065)	0.002 (0.001)	307.5 (1.25)	1.0
Lupocyclus philippinensis	0.096 (0.023)	0.023 (0.006)	21 (0.18)	11.5
Lyreidus tridentatus	0.035 (0.017)	0.003 (0.001)	40.5 (0.74)	3.0
Macrorhamphosus molleri	21.993 (9.656)	2.919 (1.292)	98.37 (1.37)	13.0
Macrorhamphosus scolopax	8.614 (2.479)	1.072 (0.312)	86.37 (0.66)	49.0
Maxillicosta whitleyi	0.003 (0.003)	0.001 (0.001)	50 (0)	0.5
Metapenaeopsis palmensis	0.001 (0.001)	< 0.001	16 (0)	0.5
Metapenaeopsis provocatoria	0.142 (0.038)	0.182 (0.057)	9.01 (0.13)	27.0
Metapenaeopsis sp.	0.001 (0.001)	< 0.001	12 (0)	0.5
Metapenaeopsis velutina	0.061 (0.018)	0.026 (0.008)	13.68 (0.3)	7.0
Metasepia pfefferi	0.009 (0.009)	0.001 (0.001)	40 (0)	0.5
Microcanthus strigatus	2.807 (0.618)	0.031 (0.007)	122.31 (0.72)	13.0
Monacanthus sp.	0.005 (0.005)	0.001 (0.001)	40 (0)	0.5
Monomitopus sp.	0.393 (0.151)	0.024 (0.007)	117.57 (2.22)	9.0
Muraenesox bagio	0.508 (0.508)	< 0.001	()	0.5
Mursia australiensis	0.378 (0.074)	0.036 (0.007)	39.54 (0.37)	19.5
Nassarius conoidalis	0.004 (0.004)	0.001 (0.001)	25 (0)	0.5
Naxioides robillardi	0.05 (0.042)	0.003 (0.002)	31.5 (0.85)	1.0
Nelusetta ayraudi	13.646 (5.009)	0.012 (0.004)	426.42 (2.36)	5.0
Nemipterus aurifilum	35.009 (4.498)	0.793 (0.195)	125.89 (1.86)	58.5
Nemipterus theodorei	4.433 (1.89)	0.052 (0.026)	151.78 (1.83)	4.0
Neocentropogon aeglefinus	5.878 (2.519)	0.27 (0.112)	76.95 (1.49)	6.5
Neocentropogon sp.	0.024 (0.024)	< 0.001	120 (0)	0.5
Neolaeops microphthalmus	0.016 (0.008)	0.001 (0.001)	115 (2.49)	2.5
Neomerinthe sp.	0.006 (0.006)	< 0.001	70 (0)	0.5
Neosebastes cf entaxis	0.324 (0.141)	0.032 (0.01)	51.41 (0.75)	12.0
Neosebastes incisipinnis	8.429 (1.835)	0.129 (0.02)	115.36 (2.12)	36.5
Nettastoma solitarium	0.077 (0.074)	0.001 (0.001)	685 (34)	1.0
Nototodarus sp.	0.214 (0.126)	0.001 (0)	196.67 (1.81)	1.5
Ocosia apia	0.001 (0.001)	< 0.001	50 (0)	0.5
Octopus australis	0.088 (0.06)	0.002 (0.001)	34.17 (0.57)	1.5
Octopus kagoshimensis	0.918 (0.542)	0.013 (0.008)	55.67 (0.76)	3.5
Octopus sp.	0.404 (0.206)	0.011 (0.003)	29.97 (1.38)	9.0
Octopus sp. *B*	0.038 (0.038)	< 0.001	42.5 (0)	0.5
Octopus sp. *G*	0.202 (0.161)	0.003 (0.002)	45.83 (1.35)	1.5
Octopus sp. *I*	0.07 (0.049)	0.002 (0.001)	37.5 (2.05)	2.0
Octopus sp. *J*	0.086 (0.086)	< 0.001	75 (0)	0.5
Odontodactylus japonicus	0.007 (0.007)	0.001 (0.001)	18 (0)	0.5
Ophichthus sp.	0.094 (0.094)	< 0.001	790 (0)	0.5
Ophidion muraenolepis	2.005 (0.726)	0.055 (0.014)	155.55 (2.9)	22.5
Optivus sp. *1*	0.726 (0.442)	0.066 (0.045)	80.03 (0.5)	7.5
Orectolobus ornatus	2.974 (2.104)	0.001 (0)	()	1.0
Ostichthys japonicus	1.336 (0.977)	0.019 (0.01)	89.58 (2.09)	3.0
Pagrus auratus	0.205 (0.205)	0.001 (0.001)	180 (0)	0.5
Pagurid sp.	0.003 (0.003)	< 0.001	19 (0)	0.5
Pagurid sp. *Z*	0.002 (0.002)	< 0.001	40 (0)	0.5
Paguropsis typica	0.076 (0.029)	0.011 (0.004)	15.5 (0.23)	4.5
Parabothus kiensis	0.011 (0.011)	0.001 (0.001)	112.5 (0)	0.5
Paradorippe australiensis	0.002 (0.002)	0.001 (0.001)	17 (0)	0.5
Paramonacanthus lowei	0.018 (0.018)	0.001 (0.001)	95 (0)	0.5
Parapenaeus sextuberculatus	0.04 (0.019)	0.032 (0.016)	11.83 (0.25)	4.0
Parapercis sp. *A*	10.943 (3.244)	0.848 (0.248)	89.5 (0.8)	16.5

Species	**Mean catch rate g ha^{-1}**	**Mean catch rate n ha^{-1}**	**Mean length mm**	**Frequency of capture (%)**
Parapercis sp. *B*	0.515 (0.173)	0.025 (0.008)	95.97 (1.25)	7.5
Parapercis sp. *C*	0.02 (0.014)	0.003 (0.002)	65 (0)	1.0
Parascyllium collare	0.064 (0.064)	< 0.001	435 (0)	0.5
Penaeus sp.	0.001 (0.001)	0.001 (0.001)	12 (0)	0.5
Peronella sp.	20.827 (3.954)	0.816 (0.128)	63.15 (1.04)	58.0
Petrarctus brevicornis	0.056 (0.027)	0.01 (0.004)	16 (0.33)	6.0
Phalangipus australiensis	0.001 (0.001)	0.001 (0.001)	13 (0)	0.5
Philine angasi	0.003 (0.003)	0.001 (0.001)	32.5 (0)	0.5
Photololigo sp.	4.514 (0.871)	0.26 (0.043)	72 (1.05)	45.0
Physiculus therosideros	0.128 (0.088)	0.005 (0.003)	117.5 (0.64)	1.5
Pike eel	0.271 (0.271)	0.001 (0.001)	625 (0)	0.5
Plagiopsetta glossa	1.136 (0.217)	0.085 (0.011)	103.31 (1.46)	34.0
Platycephalus caeruleopunctatus	4.128 (1.337)	0.009 (0.003)	351.39 (3.07)	6.0
Platycephalus longispinis	0.841 (0.451)	0.024 (0.013)	162.53 (2.12)	2.5
Platycephalus marmoratus	0.923 (0.374)	0.003 (0.001)	282.5 (3.12)	4.5
Plesionika laurentae	14.709 (2.779)	4.179 (0.806)	15.77 (0.14)	61.5
Pleuroploca australasia	0.01 (0.01)	0.001 (0.001)	60 (0)	0.5
Pontocaris orientalis	0.064 (0.02)	0.037 (0.011)	11.15 (0.1)	11.0
Portunus argentatus	1.322 (0.646)	0.283 (0.139)	30.9 (0.31)	15.5
Portunus dubius	0.001 (0.001)	< 0.001	24 (0)	0.5
Portunus pelagicus	0.088 (0.088)	0.001 (0.001)	115 (0)	0.5
Portunus rubromarginatus	0.561 (0.366)	0.03 (0.019)	44.54 (0.48)	4.5
Portunus sanguinolentus	0.148 (0.129)	0.001 (0.001)	118 (0.7)	1.0
Priacanthus macracanthus	19.629 (3.26)	0.154 (0.028)	183.85 (1.83)	36.0
Priapipilumnus nimbus	0.004 (0.002)	0.012 (0.006)	8.6 (0.03)	3.0
Prionocidaris sp.	3.721 (1.072)	0.149 (0.026)	25.5 (0.94)	32.5
Pristigenys niphonia	0.287 (0.207)	0.009 (0.004)	78.33 (3.32)	3.0
Pristilepis oligolepis	0.019 (0.016)	0.004 (0.003)	47.5 (0.25)	1.0
Psettina gigantea	1.617 (0.328)	0.274 (0.042)	80.08 (0.96)	44.0
Psettina iijimai	0.002 (0.002)	0.001 (0.001)	65 (0)	0.5
Psettina sp.	0.005 (0.003)	0.003 (0.002)	59.17 (0.27)	1.5
Pseudanthias sp.	0.609 (0.218)	0.021 (0.007)	99.28 (0.53)	5.5
Pseudorhombus dupliciocellatus	0.078 (0.078)	0.001 (0.001)	185 (0)	0.5
Pseudorhombus jenynsii	0.034 (0.034)	< 0.001	222.5 (0)	0.5
Pseudorhombus tenuirastrum	4.366 (1.135)	0.05 (0.013)	212.76 (0.94)	12.0
Pterois sp.	0.009 (0.009)	< 0.001	90 (0)	0.5
Pterois volitans	0.077 (0.04)	0.006 (0.003)	72 (0.64)	2.5
Pterygotrigla andertoni	0.858 (0.414)	0.007 (0.004)	180 (1.95)	2.5
Quollastria gonypetes	2.047 (0.387)	0.179 (0.036)	23.34 (0.21)	42.5
Randallia eburnea	0.257 (0.05)	0.034 (0.007)	23.8 (0.17)	17.5
Ranella australasia	0.012 (0.012)	0.001 (0.001)	55 (0)	0.5
Ratabulus diversidens	81.664 (7.09)	0.988 (0.077)	198.26 (1.71)	87.0
Rexea prometheoides	0.2 (0.179)	0.003 (0.003)	202.5 (0.75)	1.0
Rhinobatos typus	0.107 (0.107)	< 0.001	470 (0)	0.5
Rhynchobatus australiae	1.524 (1.524)	< 0.001		0.5
Samaris macrolepis	0.046 (0.03)	0.003 (0.002)		1.5
Satyrichthys sp.	0.047 (0.035)	0.002 (0.001)	140 (2)	1.0
Saurenchelys sp.	0.006 (0.006)	0.003 (0.003)	200 (0)	0.5
Saurida filamentosa	104.371 (11.879)	0.757 (0.113)	246.16 (3.5)	58.0
Saurida grandisquamis	26.953 (5.604)	0.058 (0.013)	387.74 (6.69)	18.5
Saurida sp.	0.076 (0.076)	0.006 (0.006)	110.83 (0)	0.5
Scomber australisicus	1.082 (0.452)	0.007 (0.002)	203.26 (2.97)	6.0
Scorpaenid sp.	0.024 (0.021)	0.003 (0.002)	55 (1)	1.0

Species	**Mean catch rate g ha^{-1}**	**Mean catch rate n ha^{-1}**	**Mean length mm**	**Frequency of capture (%)**
Scyllarus sp. *A*	0.007 (0.006)	0.002 (0.001)	16.5 (0.55)	1.0
Sea star	0.116 (0.077)	0.007 (0.004)	80 (4.72)	2.5
Sea star 1000	0.243 (0.243)	0.014 (0.014)	92.75 (0)	0.5
Sea star 101	0.276 (0.091)	0.031 (0.009)	62.49 (1.26)	9.5
Sea star 102	0.006 (0.005)	0.001 (0.001)	57.5 (2.25)	1.0
Sea star 103	0.014 (0.007)	0.003 (0.002)	61.25 (0.88)	2.0
Sea star 104	0.074 (0.068)	0.001 (0.001)	200 (0)	1.0
Sea star 107	0.079 (0.079)	0.001 (0.001)	240 (0)	0.5
Sea star 109	0.042 (0.042)	0.001 (0.001)	185 (0)	0.5
Sea star 17	0.293 (0.293)	0.003 (0.003)	140 (0)	0.5
Sea star 3	0.002 (0.002)	0.002 (0.002)	37.5 (0)	0.5
Sea star 6	0.199 (0.199)	0.012 (0.012)	94 (0)	0.5
Sea star 65	0.008 (0.004)	0.002 (0.001)	63 (1.96)	2.5
Sea star 89	0.039 (0.039)	0.001 (0.001)	135 (0)	0.5
Sea Urchin 105	0.008 (0.007)	0.001 (0.001)	42.5 (0.25)	1.0
Sea Urchin 2	0.015 (0.015)	0.001 (0.001)	50 (0)	0.5
Sea Urchin 3	0.258 (0.258)	0.006 (0.006)	58.75 (0)	0.5
Sea Urchin 300	0.064 (0.064)	0.002 (0.002)	45 (0)	0.5
Sea Urchin 6	0.026 (0.026)	0.001 (0.001)	45 (0)	0.5
Sea Urchin 68	0.099 (0.063)	0.008 (0.005)	34 (0.19)	2.0
Sea Urchin 70	0.002 (0.002)	< 0.001	35 (0)	0.5
Sea Urchin 84	1.111 (0.498)	0.011 (0.004)	120.19 (1.72)	4.0
Sepia limata	0.631 (0.106)	0.203 (0.035)	28.88 (0.29)	39.0
Sepia mestus	0.03 (0.014)	0.012 (0.006)	22.36 (0.32)	3.0
Sepia opipara	9.762 (1.132)	0.56 (0.078)	52.98 (1.44)	59.5
Sepia plangon	0.137 (0.069)	0.007 (0.003)	55.28 (0.98)	3.0
Sepia rex	0.985 (0.427)	0.033 (0.011)	53.62 (1.81)	7.5
Sepia rozella	0.201 (0.07)	0.012 (0.004)	46.67 (0.8)	6.0
Sepia smithi	0.002 (0.001)	0.001 (0.001)	21.25 (0.38)	1.0
Sepia sp.	0.093 (0.067)	0.004 (0.003)	45 (2)	1.5
Sepia whitleyana	0.123 (0.123)	0.001 (0.001)	105 (0)	0.5
Sepioloidea lineolata	1.133 (0.182)	0.086 (0.014)	27.98 (0.39)	27.0
Sergestoidea	0.002 (0.001)	0.002 (0.001)	10 (0)	1.0
Sillago flindersi	0.715 (0.528)	0.009 (0.007)	169.88 (0.3)	1.5
Sirembo metachroma	1.508 (0.366)	0.029 (0.006)	176.3 (2.37)	12.5
Solegnathus hardwickii	0.01 (0.006)	0.003 (0.001)	156.43 (1.8)	3.5
Solenocera bifurcata	0.9 (0.155)	0.222 (0.053)	17.55 (0.24)	41.0
Solenocera choprai	7.455 (1.481)	0.875 (0.179)	22.92 (0.22)	53.0
Sphenopus marsupialus	0.039 (0.027)	0.002 (0.002)	45 (0.5)	1.0
Sphyraena acutipinnis	2.334 (1.146)	0.021 (0.011)	240.61 (1.11)	5.5
Spinapsaron barbatum	0.046 (0.024)	0.008 (0.004)	74.5 (0.54)	2.5
Stellaster sp.	0.032 (0.032)	0.002 (0.002)	32.5 (0)	0.5
Stelletta sp.	4.93 (1.195)	0.276 (0.062)	33.37 (0.4)	25.5
Stomatopod larvae	0.001 (0.001)	0.001 (0.001)	23 (0)	0.5
Sympagurus sp.	0.879 (0.105)	0.301 (0.037)	12.59 (0.15)	59.0
Synagrops japonicus	0.837 (0.252)	0.065 (0.017)	82.24 (1.41)	15.0
Synchiropus rameus	0.023 (0.023)	0.001 (0.001)	105 (0)	0.5
Synodus macrops	0.856 (0.259)	0.027 (0.008)	137.28 (1.54)	7.5
Tetrosomus concatenatus	2.875 (1.142)	0.033 (0.012)	113.88 (1.29)	6.5
Thalamita intermedia	0.001 (0.001)	< 0.001	30 (0)	0.5
Thalamita sima	0.003 (0.003)	< 0.001	36 (0)	0.5
Thamnaconus hypargyreus	16.529 (4.424)	0.515 (0.138)	115.45 (0.79)	30.5
Thamnaconus tessellatus	2.112 (0.856)	0.058 (0.021)	103.05 (1.23)	11.5
Tonna variegata	0.019 (0.019)	0.001 (0.001)	65 (0)	0.5
Torquigener altipinnis	0.892 (0.354)	0.021 (0.008)	101.46 (1.26)	6.5

Species	**Mean catch rate g ha^{-1}**	**Mean catch rate n ha^{-1}**	**Mean length mm**	**Frequency of capture (%)**
Torquigener sp.	0.002 (0.002)	0.001 (0.001)	30 (0)	0.5
Trachinocephalus myops	0.6 (0.324)	0.007 (0.004)	169.33 (2.16)	2.5
Trachurus declivis	0.131 (0.072)	0.005 (0.003)	122.5 (0.46)	2.0
Trachurus novaezelandiae	9.279 (2.99)	0.159 (0.049)	146.87 (2)	11.5
Trachypenaeus curvirostris	1.202 (0.332)	0.292 (0.08)	15.96 (0.2)	21.5
Triacanthodes ethiops	0.051 (0.031)	0.01 (0.005)	43.92 (1.19)	3.0
Trygonoptera testacea	0.246 (0.246)	0.001 (0.001)		0.5
Umbraculum umbraculum	0.184 (0.184)	0.001 (0.001)	120 (0)	0.5
Unidentified Alcyonarian	0.001 (0.001)	< 0.001		0.5
Unidentified Ascidian	0.004 (0.004)	< 0.001	80 (0)	0.5
Unidentified Crinoid	0.086 (0.046)	0.02 (0.007)		5.5
Unidentified Gorgonian	0.017 (0.017)	< 0.001		0.5
Unidentified Hydroid	0.016 (0.01)	< 0.001	360 (0)	2.0
Unidentified Sponge	2.614 (0.84)	0.007 (0.004)		5.5
Unidentified Stomatopod	0.035 (0.026)	0.002 (0.001)	28.25 (0.18)	1.0
Upeneichthys lineatus	1.705 (1.355)	0.01 (0.005)	141.25 (2.49)	3.0
Upeneus tragula	0.931 (0.67)	0.033 (0.024)	102.42 (0.28)	1.5
Uranoscopus cognatus	0.012 (0.012)	0.001 (0.001)	80 (0)	0.5
Uranoscopus terraereginae	2.746 (0.922)	0.056 (0.023)	98.71 (4.62)	10.5
Uroconger lepturus	0.022 (0.022)	< 0.001	330 (0)	0.5
Urolophus kapalensis	1.037 (0.446)	0.007 (0.003)	161.56 (4.16)	4.0
Urolophus sufflavus	0.246 (0.246)	0.001 (0.001)	284 (0)	0.5
Volva volva	0.005 (0.005)	0.003 (0.003)	46 (0)	0.5
Xanthid sp.	0.087 (0.012)	0.221 (0.031)	8.27 (0.07)	30.5
Xenophora indica	0.347 (0.347)	0.021 (0.021)	39.5 (0)	0.5
Xenophora peroniana	2.027 (0.406)	0.17 (0.035)	38.68 (0.43)	21.0
Zanclistius elevatus	0.021 (0.021)	< 0.001	165 (0)	0.5
Zebrias scalaris	0.051 (0.051)	0.001 (0.001)	155 (0)	0.5
Zenopsis nebulosus	1.121 (0.523)	0.002 (0.001)	271.67 (2.53)	3.0
Zeus faber	3.115 (0.921)	0.011 (0.003)	211.67 (1.31)	6.0

Appendix 6. The mean catch rate (number m^{-2}) of bycatch species from the 2000 Long-Term Monitoring scallop fishery-independent survey. Bycatch samples were retained from one net at 122 of the 374 sites that were trawled. These species and catch rates may not necessarily be representative of the scallop fishery bycatch because the survey was undertaken using prawn nets that have smaller mesh than the scallop nets.

Rank	**Species**	**Mean catch rate (number m^{-2})**
1	*Metapenaeopsis palmensis*	0.005404
2	*Torquigener pallimaculatus*	0.004543
3	*Paramonacanthus otisensis*	0.003698
4	*Pristotis jerdoni*	0.003308
5	*Portunus rubromarginatus*	0.003173
6	*Paramonacanthus filicauda*	0.002278
7	*Upeneus asymmetricus*	0.002187
8	*Lethrinus genivittatus*	0.002049
9	*Trachypenaeus curvirostris*	0.001554
10	*Engyprosopon grandisquama*	0.001474
11	*Nemipterus theodorei*	0.001177
12	*Pentapodus nagasakiensis*	0.001063
13	*Upeneus tragula*	0.000937
14	*Saurida undosquamis*	0.000934
15	*Apistus carinatus*	0.000909
16	*Siganus fuscescens*	0.000896
17	*Callionymus limiceps*	0.000872
18	*Chlamys* sp. *1*	0.00079
19	*Trachinocephalus myops*	0.000643
20	*Lepidotrigla argus*	0.000596
21	*Metapenaeopsis lamellata*	0.000461
22	*Torquigener perlevis*	0.00042
23	*Parapercis nebulosa*	0.000378
24	*Amusium pleuronectes*	0.000343
25	*Sorsogona tuberculata*	0.000335
26	*Spatangoida* sp	0.000326
27	*Inimicus sinensis*	0.000321
28	*Apogon poecilopterus*	0.000313
29	*Apogon cf semilineata*	0.000308
30	*Parapriacanthus ransonneti*	0.000292
31	*Portunus argentatus*	0.000281
32	*Amusium balloti*	0.000258
33	*Sepia opipara*	0.000243
34	*Inegocia japonica*	0.000234
35	*Gymnocranius elongatus*	0.000233
36	*Lepidotrigla cf japonica*	0.000229
37	*Grammatobothus polyophthalmus*	0.000209
38	*Apogon nigripinnis*	0.000179
39	*Pentaceraster* sp	0.000179
40	*Euprymna* sp. *C*	0.000178
41	*Trachypenaeus granulosus*	0.000173
42	*Batrachomoeus dubius*	0.000172
43	*Sepia plangon*	0.000168
44	*Matuta inermis*	0.000166
45	*Engyprosopon macroptera*	0.000153
46	*Pseudorhombus spinosis*	0.000152
47	*Pseudorhombus dupliciocellatus*	0.000144
48	*Sepia papuensis*	0.000136
49	*Choerodon cephalotes*	0.000131
50	*Arnoglossus intermedius*	0.000129
51	*Pentapodus paradiseus*	0.000125
52	*Tetrosomus concatenatus*	0.000124
53	*Inegocia harrisii*	0.000118
54	*Onigocia spinosa*	0.000117
55	*Synchiropus rameus*	0.000116
56	*Engyprosopon* sp	0.000103
57	*Dactylopus dactylopus*	9.6E-05
58	*Synodus sageneus*	9.44E-05
59	*Callionymus japonicus*	9.42E-05
60	*Sillago ingenuua*	8.79E-05
61	*Cottapistus cottoides*	8.7E-05
62	*Synodus hoshinonis*	8.63E-05
63	*Erosa erosa*	8.52E-05
64	*Urchin* sp. *1*	8.21E-05
65	*Apogon thermalis*	7.93E-05
66	*Apogon capricornis*	6.82E-05
67	*Chaetoderma penicilligera*	6.65E-05
68	*Octopus* sp	6.56E-05
69	*Arnoglossus fisoni*	6.51E-05
70	*Ascidian* sp	6.48E-05
71	*Lepidotrigla umbrosa*	6.28E-05
72	*Portunus tenuipes*	6.26E-05
73	*Paramonacanthus lowei*	6.05E-05
74	*Sillago robusta*	5.83E-05
75	*Apogon septemstriatus*	5.73E-05
76	*Callionymus moretonensis*	5.69E-05
77	*Suggrundus macracanthus*	5.69E-05
78	*Crinoid*	5.37E-05
79	*Apogon kiensis*	5.28E-05
80	*Cynoglossus* sp	5.19E-05
81	*Dactyloptena papilio*	5.15E-05
82	*Pseudorhombus elevatus*	5.06E-05
83	*Sicyonia cristata*	4.93E-05
84	*Upeneus luzonius*	4.89E-05
85	*Elates ransonetti*	4.78E-05
86	*Liocranium praepositum*	4.66E-05
87	*Apogon brevicaudatus*	4.61E-05
88	*Arnoglossus waitei*	4.46E-05
89	*Thalamita intermedia*	4.45E-05
90	*Callionymus belcheri*	4.45E-05

Rank	**Species**	**Mean catch rate (number m^{-2})**	**Rank**	**Species**	**Mean catch rate (number m^{-2})**
91	*Portunus haanii*	4.43E-05	143	*Aseraggodes melanostictus*	1.81E-05
92	*Solenocera pectinata*	4.41E-05	144	*Sirembo imberbis*	1.79E-05
93	*Penaeus longistylus*	4.4E-05	145	*Halophryne ocellatus*	1.75E-05
94	*Scyllarus demani*	4.36E-05	146	*Portunus sanguinolentus*	1.71E-05
95	*Apogon cf fuscomaculatus*	4.35E-05	147	*Bathypilumnus pugilator*	1.7E-05
96	*Penaeus plebejus*	4.26E-05	148	*Callionymus* sp.	1.69E-05
97	*Zebrias craticula*	3.95E-05	149	*Amblyrhynchotes spinosissimus*	1.67E-05
98	*Fungia* sp.	3.88E-05	150	*Tathicarpus butleri*	1.65E-05
99	*Apogon fasciatus*	3.87E-05	151	*Uranoscopus terraereginae*	1.62E-05
100	*Brachaluteres taylori*	3.77E-05	152	*Soleichthys heterorhinos*	1.61E-05
101	*Apogon ellioti*	3.77E-05	153	*Choerodon sugillatum*	1.6E-05
102	*Dactyloptena macracanthus*	3.71E-05	154	*Sebastapistes strongia*	1.57E-05
103	*Nemipterus hexodon*	3.62E-05	155	*Lupocyclus rotundatus*	1.49E-05
104	*Platycephalus arenarius*	3.58E-05	156	*Diagramma pictum*	1.49E-05
105	*Sea urchin* sp. *3 (CSIRO)*	3.56E-05	157	*Hydroid*	1.42E-05
106	*Dendrochirus brachypterus*	3.49E-05	158	*Dasyatis kuhlii*	1.4E-05
107	*Torquigener altipinnis*	3.41E-05	159	*Euprymna* sp. *C*	1.39E-05
108	*Peronella* sp.	3.37E-05	160	*Nudibranch*	1.39E-05
109	*Portunus gracilimanus*	3.29E-05	161	*Carinosquilla australiensis*	1.38E-05
110	*Crossorhombus azureus*	3.17E-05	162	*Psettina gigantea*	1.36E-05
111	*Saurida* sp. *2*	3.06E-05	163	*Actinopyga miliaris*	1.32E-05
112	*Pseudomonacanthus peroni*	2.97E-05	164	*Pegasus volitans*	1.31E-05
113	*Ascidian*	2.96E-05	165	*Sea urchin* sp. *6 (CSIRO)*	1.27E-05
114	*Lepidotrigla grandis*	2.95E-05	166	*Carangoides malabaricus*	1.26E-05
115	*Stellaster equestris*	2.91E-05	167	*Leiognathus aureus*	1.26E-05
116	*Selaroides leptolepis*	2.87E-05	168	*Jonas leuteanus*	1.24E-05
117	*Rogadius patriciae*	2.84E-05	169	*Bivalve*	1.23E-05
118	*Anthenea* sp.	2.76E-05	170	*Tamaria* sp.	1.23E-05
119	*Sand dollar*	2.73E-05	171	*Lutjanus vittus*	1.21E-05
120	*Apogon* sp.	2.69E-05	172	*Diadema* sp.	1.16E-05
121	*Tetrosomus gibbosus*	2.69E-05	173	*Fowleria* sp.	1.16E-05
122	*Synodus indicus*	2.59E-05	174	*Scyllarus* sp. *A*	1.15E-05
123	*Pseudorhombus diplospilus*	2.53E-05	175	*Parupeneus pleurospilus*	1.14E-05
124	*Stichopus* sp.	2.5E-05	176	*Hyastenus diacanthus*	1.14E-05
125	*Aploactis aspera*	2.49E-05	177	*Sargocentron rubrum*	1.11E-05
126	*Trachypenaeus anchoralis*	2.47E-05	178	*Apogon quadrifasciatus*	1.04E-05
127	*Scyllarus* sp. *Z*	2.41E-05	179	*Terapon theraps*	1.03E-05
128	*Lethrinus laticaudus*	2.35E-05	180	*Sepia whitleyana*	1.01E-05
129	*Sepia smithi*	2.31E-05	181	*Carangoides talamparoides*	9.78E-06
130	*Basket star*	2.2E-05	182	*Euristhmus nudiceps*	9.73E-06
131	*Metasepia pfefferi*	2.2E-05	183	*Luidia maculata*	9.66E-06
132	*Choerodon venustus*	2.18E-05	184	*Photololigo* sp.	9.51E-06
133	*Charybdis jaubertensis*	2.18E-05	185	*Portunus* sp.	9.27E-06
134	*Priacanthus macracanthus*	2.15E-05	186	*Sea star* sp. *3*	9.08E-06
135	*Plotosus lineatus*	2.14E-05	187	*Urchin* sp. *2*	9.01E-06
136	*Trixiphichthys weberi*	2.13E-05	188	*Foa brachygramma*	8.99E-06
137	*Chaetodontoplus personifer*	2.08E-05	189	*Pterygotrigla hemisticta*	8.97E-06
138	*Apogon cavitiensis*	1.99E-05	190	*Upeneus moluccensis*	8.88E-06
139	*Holothuria ocellata*	1.96E-05	191	*Matuta granulosa*	8.65E-06
140	*Pseudorhombus jenynsii*	1.85E-05	192	*Paracentropogon longispinis*	8.55E-06
141	*Urchin* sp. *3*	1.83E-05	193	*Lethrinus nebulosus*	8.41E-06
142	*Thalamita sima*	1.81E-05	194	*Bohadschia marmorata*	7.96E-06

Rank	**Species**	**Mean catch rate (number m^{-2})**
195	*Diploprion bifasciatum*	7.83E-06
196	*Decapterus russellii*	7.78E-06
197	*Hyastenus* sp. *4*	7.6E-06
198	*Pentaprion longimanus*	7.55E-06
199	*Synodus variegatus*	7.48E-06
200	*Pentapodus porosus*	7.45E-06
201	*Urchin* sp. *6*	7.35E-06
202	*Dasyatis leylandi*	7.12E-06
203	*Rhynchostracion nasus*	7.09E-06
204	*Oratosquilla quinquedentata*	6.94E-06
205	*Carid* sp.	6.9E-06
206	*Lactoria cornutus*	6.61E-06
207	*Petroscirtes lupus*	6.35E-06
208	*Pseudochromis quinquedentatus*	6.27E-06
209	*Coris caudimacula*	6.27E-06
210	*Alcyonarian*	6.13E-06
211	*Abalistes stellaris*	5.95E-06
212	*Parupeneus barberoides*	5.94E-06
213	*Sea star* sp. *14*	5.89E-06
214	*Bodianus vulpinus*	5.84E-06
215	*Centriscus scutatus*	5.77E-06
216	*Pterocaesio diagramma*	5.72E-06
217	*Leucosia ocellata*	5.69E-06
218	*Sand ascidian*	5.68E-06
219	*Valenciennea* sp.	5.48E-06
220	*Portunus* sp. *1*	5.4E-06
221	*Strabozebrias cancellatus*	5.38E-06
222	*Lagocephalus sceleratus*	5.38E-06
223	*Gorgonian*	5.28E-06
224	*Antennarius striatus*	5.26E-06
225	*Sepioloidea lineolata*	5.25E-06
226	*Scorpaenopsis* sp. *B*	5.21E-06
227	*Lutjanus adetti*	5.1E-06
228	*Sepiadarium austrinium*	5.08E-06
229	*Pseudorhombus arsius*	5.04E-06
230	*Cypselurus* sp.	4.98E-06
231	*Sepia mestus*	4.94E-06
232	*Caluactaea tumida*	4.81E-06
233	*Dendrochirus zebra*	4.81E-06
234	*Paraploactis* sp.	4.81E-06
235	*Trygonoptera testacea*	4.69E-06
236	*Sea star* sp. *99*	4.51E-06
237	*Chaetodontoplus meredithi*	4.5E-06
238	*Chlamys* sp. *2*	4.45E-06
239	*Lutjanus malabaricus*	4.4E-06
240	*Astropecten* sp.	4.39E-06
241	*Sepia* sp.	4.17E-06
242	*Cirrhitichthys aprinus*	3.92E-06
243	*Anchisomus multistriatus*	3.9E-06
244	*Scorpaenodes smithi*	3.88E-06
245	*Cottapistus praepositus*	3.81E-06
246	*Ibacus brucei*	3.7E-06
247	*Epinephelus sexfasciatus*	3.67E-06
248	*Aptychotrema rostrata*	3.65E-06
249	*Bryozoan*	3.61E-06
250	*Samaris macrolepis*	3.53E-06
251	*Peristrominous dolosus*	3.52E-06
252	*Holothurian* sp. *3*	3.48E-06
253	*Rhynchoconger cf ectenurus*	3.46E-06
254	*Parapenaeus longipes*	3.41E-06
255	*Charybdis natator*	3.37E-06
256	*Arothron aerostaticus*	3.35E-06
257	*Platycephalus endrachtensis*	3.33E-06
258	*Thenus indicus*	3.28E-06
259	*Apogon limenus*	3.25E-06
260	*Gonodactylus graphurus*	3.23E-06
261	*Lophopilumnus globosus*	3.21E-06
262	*Pentaceraster regularis*	3.21E-06
263	*Castostylus mosaicus*	3.2E-06
264	*Saurida filamentosa*	3.14E-06
265	*Parascorpaena picta*	3.13E-06
266	*Aesopia cornuta*	3.13E-06
267	*Ablabys taenianotus*	3.07E-06
268	*Portunus pelagicus*	3.07E-06
269	*Leiognathus bindus*	3.05E-06
270	*Diodon holacanthus*	2.92E-06
271	*Parapercis clathrata*	2.92E-06
272	*Scorpaenopsis venosa*	2.92E-06
273	*Aploactinidae* sp. *1 (undescribed)*	2.9E-06
274	*Fistularia petimba*	2.85E-06
275	*Cociella crocodila*	2.85E-06
276	*Lutjanus sebae*	2.81E-06
277	*Pomadasys maculatum*	2.8E-06
278	*Suezichthys gracilis*	2.76E-06
279	*Solegnathus* cf. *hardwickii*	2.73E-06
280	*Cyclichthys jaculiferus*	2.71E-06
281	*Myra* sp. *B*	2.68E-06
282	*Phalangipes* sp. *1*	2.67E-06
283	*Choerodon cf frenatus*	2.65E-06
284	*Suggrundus jugosus*	2.62E-06
285	*Euretaster insignis*	2.62E-06
286	*Micippa* sp.	2.62E-06
287	*Sea star* sp. *A*	2.62E-06
288	*Sea star* sp. *B*	2.62E-06
289	*Sepioteuthis lessoniana*	2.59E-06
290	*Kanekonia queenslandica*	2.59E-06
291	*Suezichthys devisi*	2.56E-06
292	*Uranoscopus cognatus*	2.56E-06
293	*Thalamita oculea*	2.54E-06
294	*Urchin* sp. *10*	2.54E-06
295	*Monacanthus chinensis*	2.5E-06
296	*Pteragogus amboinensis*	2.49E-06
297	*Pseudomonacanthus elongatus*	2.49E-06

Rank	**Species**	**Mean catch rate (number m^{-2})**
298	*Gastropod* sp. *AA*	2.47E-06
299	*Charybdis bimaculata*	2.45E-06
300	*Dromid* sp. *A*	2.44E-06
301	*Pilumnid* sp. *D*	2.44E-06
302	*Pentacta anceps*	2.42E-06
303	*Priacanthus hamrur*	2.39E-06
304	*Stolephorus* sp.	2.39E-06
305	*Coradion chrysozonus*	2.32E-06
306	*Arothron stellatus*	2.28E-06
307	*Cynoglossus bilineatus*	2.23E-06
308	*Temnopleurus* sp.	2.22E-06
309	*Nemipterus furcosus*	2.2E-06
310	*Charybdis miles*	2.2E-06
311	*Charybdis truncata*	2.15E-06
312	*Engraulis australis*	2.06E-06
313	*Goniasteridae*	2.05E-06
314	*Holothurian* sp. *102*	2.04E-06
315	*Antennarius hispidus*	2.01E-06
316	*Minous trachycephalus*	2E-06
317	*Chaetodontoplus duboulayi*	1.98E-06
318	*Hyastenus* sp. *6*	1.98E-06
319	*Paramonacanthus elongatus*	1.98E-06
320	*Zebrias quagga*	1.96E-06
321	*Sea pen*	1.93E-06
322	*Sea urchin* sp. *68*	1.92E-06
323	*Quallastria gonypetes*	1.91E-06
324	*Penaeus esculentus*	1.9E-06
325	*Cymbacephalus nematophthalmus*	1.87E-06
326	*Microcanthus strigatus*	1.87E-06
327	*Scolopsis monogramma*	1.87E-06
328	*Sea star* sp. *13*	1.87E-06
329	*Penaeus latisulcatus*	1.84E-06
330	*Pseudorhombus spinosus*	1.8E-06
331	*Stellaster* sp.	1.8E-06
332	*Metapenaeopsis* sp.	1.79E-06
333	*Pseudorhombus quinquocellatus*	1.78E-06
334	*Minous versicolor*	1.77E-06
335	*Charybdis yaldwyni*	1.71E-06
336	*Portunus rugosus*	1.67E-06
337	*Atergatopsis* sp. *1*	1.6E-06
338	*Gaillardielus ruepelli*	1.6E-06
339	*Pilumnus* sp. *X*	1.6E-06
340	*Porcellanid s. p6*	1.6E-06
341	*Rhabdamia cypselurus*	1.6E-06
342	*Odontodactylus* sp.	1.54E-06
343	*Philine* sp.	1.54E-06
344	*Pilumnus semilanatus*	1.54E-06
345	*Portunus granulatus*	1.51E-06
346	*Urchin* sp. *5*	1.5E-06
347	*Torquigener whitleyi*	1.46E-06
348	*Arcania* sp.	1.43E-06
349	*Oratosquilla inornata*	1.4E-06
350	*Lupocyclus phillipinensis*	1.4E-06
351	*Rhinobatus typus*	1.38E-06
352	*Hapalochlaena lunulata*	1.38E-06
353	*Parupeneus* sp.	1.38E-06
354	*Banareia* sp.	1.34E-06
355	*Paraplagusia unicolor*	1.33E-06
356	*Fraudella carassiops*	1.32E-06
357	*Aulostomus chinensis*	1.29E-06
358	*Liocarcinus corrugatus*	1.27E-06
359	*Urchin* sp.	1.26E-06
360	*Eurypegasus draconis*	1.26E-06
361	*Pilumnid* sp. *C*	1.26E-06
362	*Choerodon zamboangae*	1.26E-06
363	*Carangoides* sp.	1.25E-06
364	*Choerodon monostigma*	1.25E-06
365	*Apogon coccineus*	1.25E-06
366	*Harrouia* sp. *3*	1.25E-06
367	*Cryptopodia* sp. *1*	1.24E-06
368	*Cryptopodia* sp. *2*	1.24E-06
369	*Sicyonia rectirostris*	1.24E-06
370	*Charybdis* sp.	1.21E-06
371	*Dromid* sp. *A*	1.18E-06
372	*Glossanodon* sp.	1.18E-06
373	*Dorippe quadridens*	1.16E-06
374	*Ichthyscopus insperatus*	1.16E-06
375	*Scorpaenoides varippinnis*	1.15E-06
376	*Raniniidae* sp.	1.06E-06
377	*Hypodistoma* sp.	1.04E-06
378	*Scorpaenopsis* sp. *A*	1.04E-06
379	*Lepidotrigla callodactyla*	9.86E-07
380	*Saurida micropectoralis*	9.86E-07
381	*Urchin* sp. *68*	9.86E-07
382	*Stellaster* sp. *2*	9.6E-07
383	*Herklotsichthys lippa*	9.5E-07
384	*Pilumnid* sp. *A*	8.97E-07
385	*Dardanus* sp. *E*	8.96E-07
386	*Epinephelus undulostriatus*	8.96E-07
387	*Hyastenus* sp. *1*	8.96E-07
388	*Ogilbia* sp.	8.96E-07
389	*Etrumeus teres*	8.32E-07
390	*Oratosquilla interrupta*	8.3E-07
391	*Pterois volitans*	8.09E-07
392	*Coccotropus* sp.	7.78E-07
393	*Hyastenus cambelli*	7.78E-07
394	*Pseudorhombus argus*	7.78E-07
395	*Centropogon* sp.	7.73E-07
396	*Pomacentridae*	7.73E-07
397	*Lophopilumnus* sp.	7.7E-07
398	*Majidae* sp. *1*	7.36E-07
399	*Leiognathus moretoniensis*	6.87E-07
400	*Pontocaris orientalis*	6.5E-07

Rank	**Species**	**Mean catch rate (number m^{-2})**
401	*Apolectus niger*	6.3E-07
402	*Gnathophis* sp.	6.3E-07
403	*Zabidius novaemaculatus*	6.3E-07
404	*Upeneichthys lineatus*	6.24E-07
405	*Urchin* sp. *11 (CSIRO)*	6.24E-07
406	*Jonas* sp.	5.97E-07
407	*Metapenaeus ensis*	5.97E-07
408	*Thenus orientalis*	5.97E-07
409	*Rastrelliger brachysoma*	5.82E-07
410	*Aipysurus laevis*	2.52E-07
411	*Lapemis hardwickii*	1.91E-07
412	*Hydrophis elegans*	1.85E-07
413	*Trachyrhamphus biaculeatus*	1.82E-07

Appendix 7. List of all Syngnathids caught from 1619 individual nets trawls obtained during the project. Details of the sector, fishing trip, trip shot and net where each individual was obtained, and the total length of the individual, are provided.

Trawl Sector	Trip	Trip shot	Net	Species	Length (mm)
Tiger/endeavour	2	19	Outer Starboard	*Filicampus tigrus*	275
Tiger/endeavour	2	20	Inner Port	*Filicampus tigrus*	255
Tiger/endeavour	2	35	Inner Starboard	*Filicampus tigrus*	271
Tiger/endeavour	2	43	Outer Starboard	*Hippocampus queenslandicus*	55
Eastern King Prawn	59	17	Port	*Hippocampus queenslandicus*	90
Eastern King Prawn	59	39	Starboard	*Hippocampus queenslandicus*	85
Eastern King Prawn	59	41	Port	*Hippocampus queenslandicus*	120
Eastern King Prawn	59	51	Port	*Hippocampus queenslandicus*	125
Eastern King Prawn	59	16	Port	*Solegnathus dunckeri*	130
Eastern King Prawn	59	16	Port	*Solegnathus dunckeri*	115
Eastern King Prawn	52	2	Port	*Solegnathus cf. hardwickii*	195
Eastern King Prawn	52	10	Port	*Solegnathus cf. hardwickii*	355
Eastern King Prawn	58	1	Port	*Solegnathus cf. hardwickii*	140
Eastern King Prawn	58	2	Port	*Solegnathus cf. hardwickii*	140
Eastern King Prawn	58	3	Starboard	*Solegnathus cf. hardwickii*	140
Eastern King Prawn	58	3	Starboard	*Solegnathus cf. hardwickii*	140
Eastern King Prawn	58	4	Starboard	*Solegnathus cf. hardwickii*	185
Eastern King Prawn	58	4	Starboard	*Solegnathus cf. hardwickii*	185
Eastern King Prawn	58	6	Port	*Solegnathus cf. hardwickii*	165
Eastern King Prawn	58	6	Port	*Solegnathus cf. hardwickii*	165
Eastern King Prawn	58	8	Port	*Solegnathus cf. hardwickii*	130
Eastern King Prawn	58	8	Port	*Solegnathus cf. hardwickii*	130
Eastern King Prawn	59	7	Port	*Solegnathus cf. hardwickii*	342
Eastern King Prawn	59	8	Port	*Solegnathus cf. hardwickii*	342
Eastern King Prawn	59	8	Port	*Solegnathus cf. hardwickii*	364
Eastern King Prawn	59	10	Port	*Solegnathus cf. hardwickii*	270
Eastern King Prawn	59	10	Port	*Solegnathus cf. hardwickii*	281
Eastern King Prawn	59	10	Port	*Solegnathus cf. hardwickii*	256
Eastern King Prawn	59	10	Port	*Solegnathus cf. hardwickii*	250
Eastern King Prawn	59	10	Port	*Solegnathus cf. hardwickii*	259
Eastern King Prawn	59	10	Port	*Solegnathus cf. hardwickii*	254
Eastern King Prawn	59	10	Port	*Solegnathus cf. hardwickii*	230
Eastern King Prawn	59	10	Port	*Solegnathus cf. hardwickii*	209
Eastern King Prawn	59	10	Port	*Solegnathus cf. hardwickii*	210
Eastern King Prawn	59	10	Starboard	*Solegnathus cf. hardwickii*	245
Eastern King Prawn	59	11	Port	*Solegnathus cf. hardwickii*	230
Eastern King Prawn	59	11	Port	*Solegnathus cf. hardwickii*	273
Eastern King Prawn	59	11	Port	*Solegnathus cf. hardwickii*	220
Eastern King Prawn	59	11	Port	*Solegnathus cf. hardwickii*	175
Eastern King Prawn	59	11	Starboard	*Solegnathus cf. hardwickii*	200
Eastern King Prawn	59	11	Starboard	*Solegnathus cf. hardwickii*	235
Eastern King Prawn	59	11	Starboard	*Solegnathus cf. hardwickii*	190
Eastern King Prawn	59	13	Port	*Solegnathus cf. hardwickii*	209
Eastern King Prawn	59	13	Port	*Solegnathus cf. hardwickii*	247
Eastern King Prawn	59	13	Port	*Solegnathus cf. hardwickii*	285
Eastern King Prawn	59	13	Port	*Solegnathus cf. hardwickii*	253
Eastern King Prawn	59	13	Port	*Solegnathus cf. hardwickii*	166
Eastern King Prawn	59	13	Port	*Solegnathus cf. hardwickii*	262

Trawl Sector	Trip	Trip shot	Net	Species	Length (mm)
Eastern King Prawn	59	14	Port	*Solegnathus cf. hardwickii*	337
Eastern King Prawn	59	14	Port	*Solegnathus cf. hardwickii*	185
Eastern King Prawn	59	14	Port	*Solegnathus cf. hardwickii*	262
Eastern King Prawn	59	14	Port	*Solegnathus cf. hardwickii*	269
Eastern King Prawn	59	14	Port	*Solegnathus cf. hardwickii*	231
Eastern King Prawn	59	14	Port	*Solegnathus cf. hardwickii*	236
Eastern King Prawn	59	14	Port	*Solegnathus cf. hardwickii*	266
Eastern King Prawn	59	14	Port	*Solegnathus cf. hardwickii*	247
Eastern King Prawn	59	14	Starboard	*Solegnathus cf. hardwickii*	205
Eastern King Prawn	59	14	Port	*Solegnathus cf. hardwickii*	190
Eastern King Prawn	59	15	Starboard	*Solegnathus cf. hardwickii*	263
Eastern King Prawn	59	15	Starboard	*Solegnathus cf. hardwickii*	231
Eastern King Prawn	59	15	Starboard	*Solegnathus cf. hardwickii*	205
Eastern King Prawn	59	15	Starboard	*Solegnathus cf. hardwickii*	251
Eastern King Prawn	59	15	Starboard	*Solegnathus cf. hardwickii*	258
Eastern King Prawn	59	15	Port	*Solegnathus cf. hardwickii*	219
Eastern King Prawn	59	15	Port	*Solegnathus cf. hardwickii*	210
Eastern King Prawn	59	15	Port	*Solegnathus cf. hardwickii*	216
Eastern King Prawn	59	15	Port	*Solegnathus cf. hardwickii*	200
Eastern King Prawn	59	16	Port	*Solegnathus cf. hardwickii*	228
Eastern King Prawn	59	16	Port	*Solegnathus cf. hardwickii*	254
Eastern King Prawn	59	16	Port	*Solegnathus cf. hardwickii*	242
Eastern King Prawn	59	16	Port	*Solegnathus cf. hardwickii*	172
Eastern King Prawn	59	16	Port	*Solegnathus cf. hardwickii*	214
Eastern King Prawn	59	16	Port	*Solegnathus cf. hardwickii*	176
Eastern King Prawn	59	16	Port	*Solegnathus cf. hardwickii*	153
Eastern King Prawn	59	16	Starboard	*Solegnathus cf. hardwickii*	253
Eastern King Prawn	59	16	Starboard	*Solegnathus cf. hardwickii*	245
Eastern King Prawn	59	16	Starboard	*Solegnathus cf. hardwickii*	168
Eastern King Prawn	59	16	Starboard	*Solegnathus cf. hardwickii*	242
Eastern King Prawn	59	16	Starboard	*Solegnathus cf. hardwickii*	153
Eastern King Prawn	59	16	Starboard	*Solegnathus cf. hardwickii*	169
Eastern King Prawn	59	16	Starboard	*Solegnathus cf. hardwickii*	177
Eastern King Prawn	59	16	Starboard	*Solegnathus cf. hardwickii*	220
Eastern King Prawn	59	17	Starboard	*Solegnathus cf. hardwickii*	157
Eastern King Prawn	59	17	Port	*Solegnathus cf. hardwickii*	191
Eastern King Prawn	59	18	Port	*Solegnathus cf. hardwickii*	164
Eastern King Prawn	59	18	Port	*Solegnathus cf. hardwickii*	145
Eastern King Prawn	59	18	Port	*Solegnathus cf. hardwickii*	145
Eastern King Prawn	59	22	Port	*Solegnathus cf. hardwickii*	207
Eastern King Prawn	59	23	Starboard	*Solegnathus cf. hardwickii*	185
Eastern King Prawn	59	25	Starboard	*Solegnathus cf. hardwickii*	276
Eastern King Prawn	59	30	Starboard	*Solegnathus cf. hardwickii*	172
Eastern King Prawn	59	49	Port	*Solegnathus cf. hardwickii*	205
Eastern King Prawn	63	14	Starboard	*Solegnathus cf. hardwickii*	335
Eastern King Prawn	63	41	Port	*Solegnathus cf. hardwickii*	205
Scallop	102	1	Outer Port	*Solegnathus cf. hardwickii*	380
Scallop	106	30	Outer Port	*Solegnathus cf. hardwickii*	440
Scallop	106	37	Inner Starboard	*Solegnathus cf. hardwickii*	402
Scallop	106	42	Outer Starboard	*Solegnathus cf. hardwickii*	478
Scallop	106	43	Outer Port	*Solegnathus cf. hardwickii*	470

Appendix 8

Marine and Freshwater Resources Institute

Age estimates of two species of threadfin bream (*Nemipterus theodorei* and *N. aurifilum)*

Final Report to the

Queensland Department of Primary Industries

Corey Green and Kyne Krusic-Golub

November 2002

State Government Victoria
Department of
Natural Resources
and Environment

Age estimation of two species of threadfin bream (*Nemipterus theodorei and Nemipterus aurifilum)*

Investigating unit: Central Ageing Facility
Address: Marine and Freshwater Resources Institute
P.O. Box 114
Queenscliff, Vic 3225
Tel: (03) 5258 0111 Fax: (03) 5258 0270
Email: corey.green@nre.vic.gov.au

SUMMARY

James Haddy from the Southern Fisheries Centre (Queensland Department of Primary Industries, QLD) approached the Central Ageing Facility (CAF), Marine and Freshwater Resources Institute, to provide annual age estimates of two species of threadfin breams (*Nemipterus theodorei* and *N. aurifilum*). A total of 314 and 186 *N. theodorei* and *N. aurifilum* sagittal otoliths collected from *N. theodorei* and *N. aurifilum* respectively, were sent for age estimation. Age estimates were determined by counting incremental structure on transversely sectioned otoliths. Estimates revealed that both species were relatively short lived. Ages ranged from 0 to 6 years for *N. theodorei* and 0 and 4 years for *N. aurifilum*. Repeated readings of otoliths from both species indicate a high level of precision.

METHODS

Samples

Initially, otoliths from a total of nine *N. theodorei* were sent to the CAF for examination to determine whether age estimates were possible. On the basis of the initial examination, the CAF was contracted to provide age estimates for a larger sample of *N. theodorei* and *N. aurifilum*. A total of 314 *Nemipterus theodorei* and 186 *N. aurifilum* sagittal otolith pairs were forwarded to the CAF for age estimation. Otoliths were stored dry in numbered envelopes with accompanying date of capture information. No other biological details were provided.. The samples arrived at the CAF and were registered in July 2002. Samples were allocate a unique identification code and registered according to Morison et al. (1998). Either the left or right otoliths were weighed to the nearest milligram, on the assumption that there was no significant difference between left and right otoliths.

Otolith preparation

Both *N. theodorei* and *N. aurifilum* were prepared using identical methods.
An initial examination of *N. theodorei* indicated that otoliths were best viewed when they were transversely sectioned as opposed to viewing them whole. The otoliths were embedded in clear polyester casting resin in rows of five. The resin blocks were oven cured at 55°C for 24 hours.

Otolith sections were cut using a Gemmasta™ lapidary saw fitted with a diamond-impregnated blade. From each row of otoliths, four sections were attained (approximately 350μm in thickness) to ensure the primordium of each otolith was included. Sections were cleaned using alcohol and stored in vials. For identification, each vial contained a numbered label.

Cleaned sections were mounted in polyester resin on glass slides (50 x 75 mm) under glass coverslips. Slides were oven cured at 30°C for a minium of 3 hours.

Reading Protocol

Sections were viewed using a dissecting microscope at a magnification of 10x (16x primary and 0.63x secondary objective) illuminated with transmitted light. Before attempting to assign age estimates the reader first became familiar with otolith structure by making a preliminary examination of the samples. Age was estimated by counting the number of complete zones (translucent – opaque sequence) on either the dorsal or ventral side; whichever displayed the highest clarity. A customised image analysis system (Morison et al., 1998) was used to mark and count increments along the ageing transect. The image analysis system was also used to measure the distance from the primordium to each of the increments. Measurement were made along a transect on the ventral side adjacent to the sulcus. The otolith margin was classified as either wide or narrow relative to the previously completed zone. Other information recorded in the Excel spreadsheet was a readability score. This is a subjective measure of the sample's readability based on the combination of the quality of the preparation and the clarity of the increments (Table 1). To avoid potential bias, all counts were made without knowledge of otolith weight.

Table 1. Interpretation of readability scores.

Score	Interpretation
1	Sample has excellent readability, increments exceptionally clear
2	Sample is unambiguous but not as clear as 1
3	Sample may be subject to two interpretations
4	Sample is subject to multiple interpretations
5	Sample is unreadable

As increment deposition and spawning duration usually occur over a period of months, a simple count of increments would most likely allocate a fish to an incorrect cohort. To assign an increment count to a particular age class, the following criterion was adopted.

A birthday of September 1 was assigned to *N. theodorei.* This date was chosen because it:

- confirms to the best knowledge of the timing of spawning (Rao, 1986)
- is also similar to the time of increment deposition (based on analysing increment width in relation to month of capture).

Plotting the month of capture against otolith weight collected from juvenile fish (<1yr) can give an approximate indication of the spawning period. A broad spawning period may be indicated by similar otolith weights distributed over an extended time interval (months).

The spawning time and increment formation for *N. aurifilum* was unknown so the same birthday allocated to *N. theodorei* (1st September) was used.

If a fish was caught between April and August with a recently formed increment (narrow edge), then Age Class = Increment Count -1 (as the fish was caught before the birthday and the increment was just formed).

If a fish was caught between April and August with a wide edge, then Age Class = Increment Count (as the fish was caught before the birthday).

If a fish was caught between September and March with a recently formed increment (narrow edge) then Age Class = Increment Count (as the fish was caught after the birthday with a recently formed increment).

If a fish was caught between September and March with a wide edge, then Age Class = Increment Count +1 (as the fish was caught after the birthday and an increment would be forming but not quite visible).

For otoliths that did not possess an increment and were presumed to be less than one year of age, a 0+ age class was assigned.

Using the above criteria, samples were assigned to the appropriate age class during ageing.

Comparison of age estimates

Repeated readings of the same otoliths provide a measure of intra-reader and inter-reader variability. They do not validate the assigned ages but provide an indication of the size of the error to be expected with a set of age estimates, due to variation in otolith interpretation. Beamish and Fournier (1981) have developed an index of average per cent error (IAPE), which has become a common method for quantifying this variation. The IAPE is calculated as:

$$IAPE = \frac{100}{N}\sum_{j=1}^{N}\left[\frac{1}{R}\sum_{i=1}^{R}\frac{|X_{ij}-X_j|}{X_j}\right]$$

where N is the number of fish aged, R is the number of times fish are aged, X_{ij} is the ith determination for the jth fish, and X_j is the average estimated age of the jth fish. The index has the property that differences in age estimates for younger fish will contribute more to the final value than will the same absolute error for older fish (Anderson et al., 1992).

To establish confidence intervals to these estimates of precision, a bootstrap technique was employed on the individual error estimates following methods described by Efron and Tibshirani (1993). Five thousand samples of error estimates (each the same size as the original) were randomly taken with replacement from the repeat readings, and a new IAPE calculated for each. The mean of these replicate IAPE's is the mean bootstrap IAPE. The bootstrap procedure exaggerates any bias present in the original estimate, so it is necessary to correct for this by adding the difference between the original statistic and the bootstrap mean, to the original estimate. The bias-corrected bootstrapped IAPE is thus calculated as:

Bias-corrected IAPE = Original IAPE + (Original IAPE- Mean Bootstrap IAPE)

The 95% confidence interval was calculated as:
95 % C.I. = Bias-corrected IAPE ± (1.96 Standard deviation of Mean Bootstrap IAPE)*

According to CAF protocol, a minimum of 25% of samples were re-read by the same reader. Precision estimates were compared with the acceptable level of agreement between readings (Morison et al., 1998). An age bias plot (Campana *et al* 1995) was used to indicate any systematic bias in the repeated age estimates. The distribution of differences between repeat readings was also inspected as another indicator of ageing error, and bias between readings.

RESULTS

Nemipterus theodorei

Transverse sections of *N. theodorei* displayed relatively clear increments from the primordium to the edge of either the dorsal or ventral sides (Figure 1) The relative position of the first increment when compared to the position of primordium varied considerably between samples. The average readability score was 2.2.

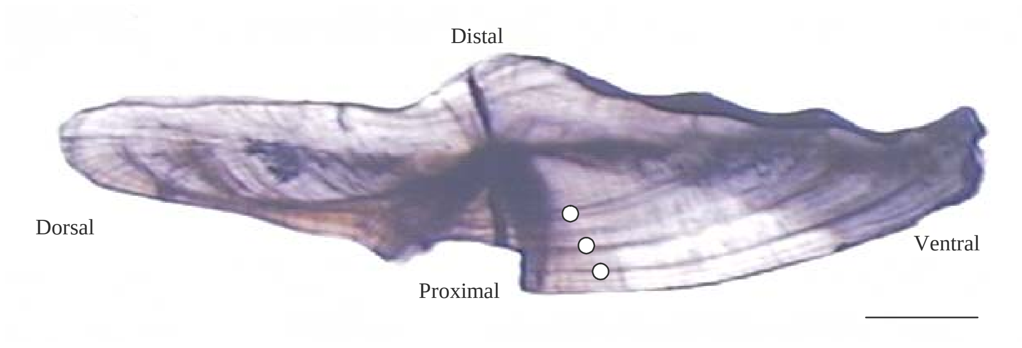


Figure 1. A transverse section of a *N. theodorei* otolith viewed with transmitted light. White circles indicate position of presumed annual increments. Scale bar =1mm

Age estimates were attained for all samples. Age classes from 0+ to 6+ years were present in the sample. The modal age class was 2+ with 97% of the entire sample less than 3 years (Figure 2).

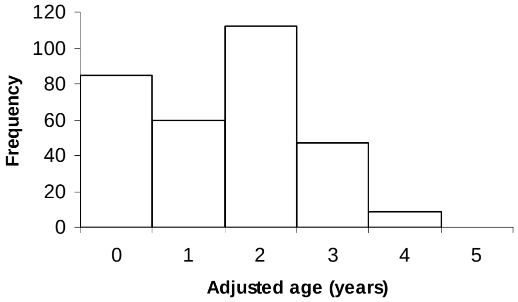


Figure 2. Age frequency distribution of *N. theodorei*. N=314

The distribution between otolith weight and month of capture is depicted in Figure 3. The figure indicates that juvenile fish with otolith weights approximately 0.01g were caught between September and February.

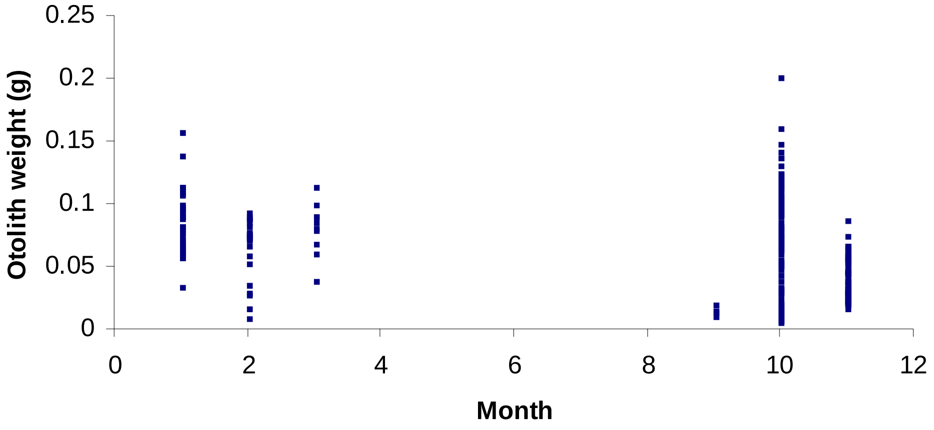


Figure 3. The distribution of otolith weight by month for *N. theodorei*.

A total of 80 preparations were re-aged to determine the level of precision surrounding the estimates. The bias corrected bootstrap mean IAPE was 3.63% (C.I. 1.53% – 5.74%). The distribution of differences between first and second readings is represented in Figure 4.

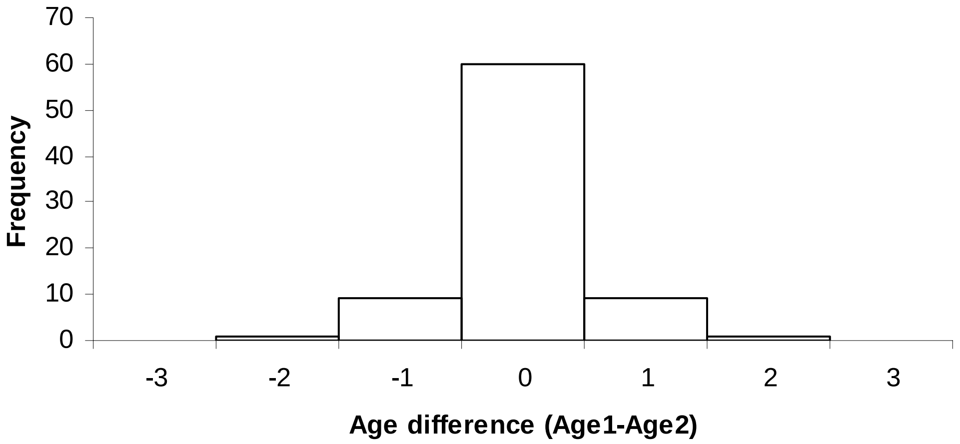


Figure 4. Distribution of differences between first and second age estimate on a sub-sample of 80 *N. theodorei* otoliths.

The level of agreement between first and second age estimates was high. Seventy-five per cent of second age estimates agreed with the first estimates obtained. Ninety-seven per cent were within one year and 100% were within two years (Table 2).

Table 2. Frequency of differences between repeated age estimates by first age estimate for *N. theodorei*

	Age1						
Age1-Age2	0	1	2	3	4	Total	%
-2		1				1	1%
-1	3	1	3	2		9	11%
0	**17**	**16**	**25**	**2**		**60**	**75%**
1		4	2	2	1	9	11%
2			1			1	1%
Total	20	22	31	6	1	80	

The relationship between otolith weight and adjusted fish age is Figure 5.

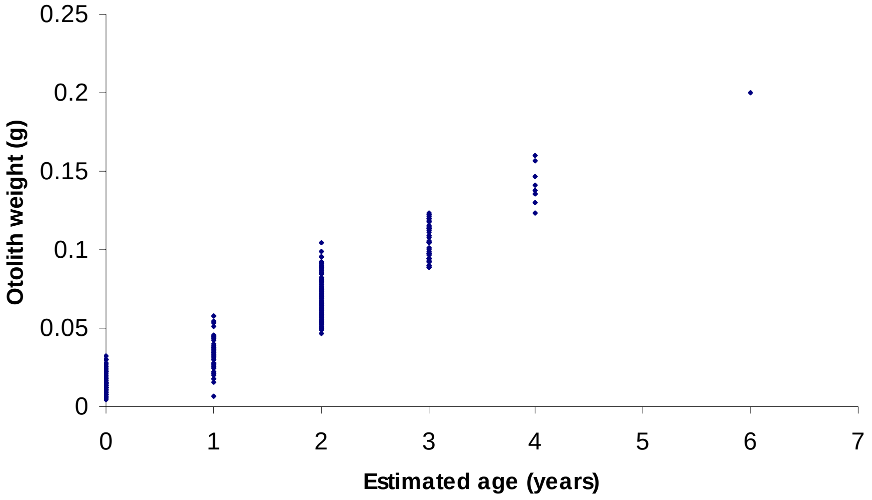


Figure 5. The relationship between adjusted fish age and otolith weight for *N. theodorei*.

Nemipterus aurifilum

Transversely sectioned otoliths from *N. aurifilum* were similar to *N. theodorei* in incremental clarity and morphological structure. Otolith structure and morphological characteristics are shown in Figure 6. This figure indicates a ‘kink’ in the sub-cupular meshwork fibre zone (SMF) and the change in direction of otolith growth along the ventral-distal surface used to help determine the position of the first increment. A feature known as the subcupular meshwork fibre zone has been useful for identifying the relative position of the first increment in snapper (Francis. et al. 1992), and can be seen in other species.

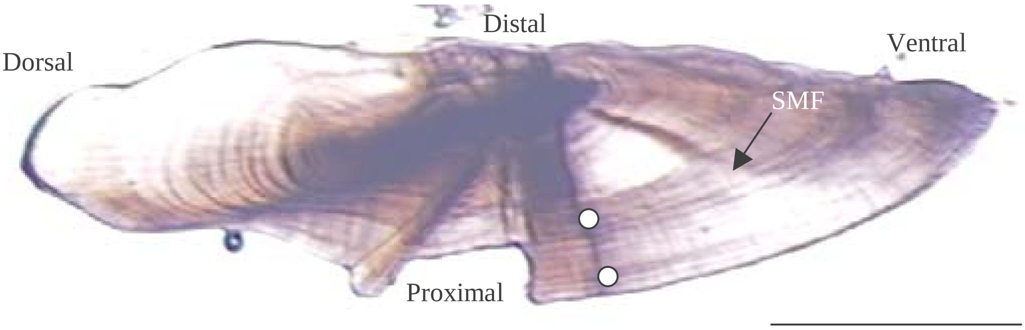


Figure 6. A transverse section of a *N. aurifilum* otolith viewed with transmitted light. White circles indicate position of presumed annual increments. Scale bar =1mm

Age was estimated for 98 % of the sample examined. Estimates for *N. aurifilum* ranged between 0+ and 4+ years. The age frequency distribution (Figure 7) indicates a modal age class of 1+ with the majority of the fish between 0+ and 2+ years.

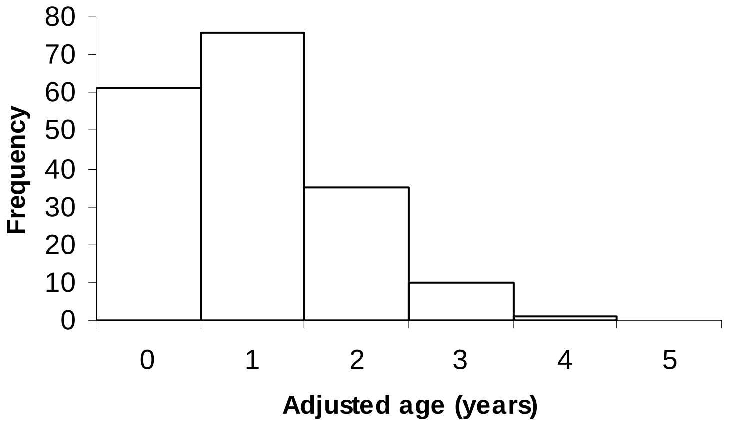


Figure 7. Age frequency distribution of *N. aurifilum*. N=183.

Figure 8. illustrates the distribution between otolith weight and month of capture. Samples were caught throughout the year with similar sized small otoliths (<0.01g otolith weight) represented. Since it was difficult to set a birthday for this species based on date of capture and spawning time, the birthday that was allocated to *N. theodorei* was used (1st September)

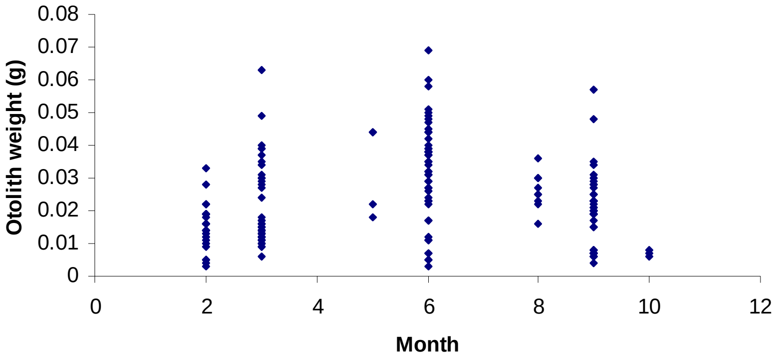


Figure 8. The distribution of otolith weight by month for *N. aurifilum*

A total of 54 *N. aurifilum* preparations were re-aged to determine the level of precision. The distribution of differences is illustrated in (Figure 9). Second age estimates agreed with the first estimates obtained for 78% of samples re-aged. All re-aged preparations were within one year. The bias corrected bootstrap mean IAPE was 5.09% (C.I. 2.01% – 8.18%).

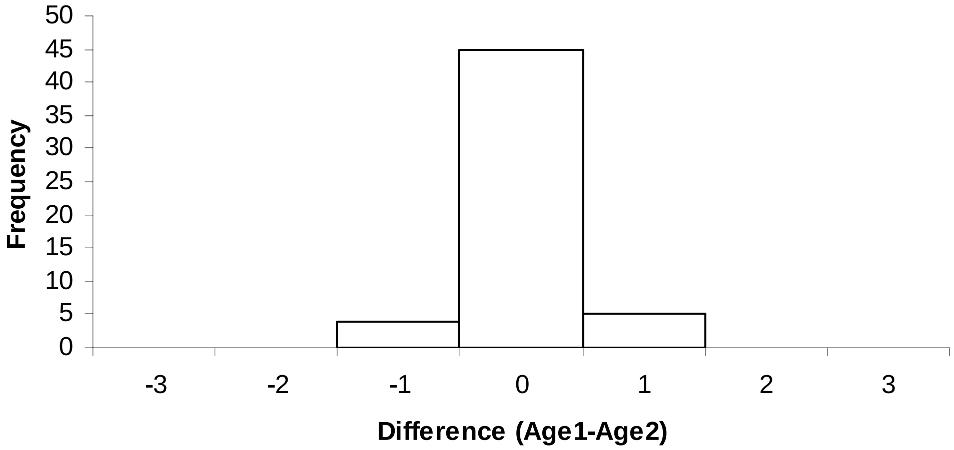


Figure 9. Distribution of differences between first and second age estimate on a sub-sample of 54 *N. aurifilum* otoliths.

Table 3. Frequency of differences between repeated age estimates by first age estimate for *N. aurifilum.*

	Age1					
Age1-Age2	0	1	2	3	Total	%
-1	3	3	1		7	13%
0	**19**	**15**	**7**	**1**	**42**	**78%**
1		5			5	9%
Total	22	23	8	1	54	

The relationship between otolith weight and adjusted and estimated fish age is depicted in Figure 10.

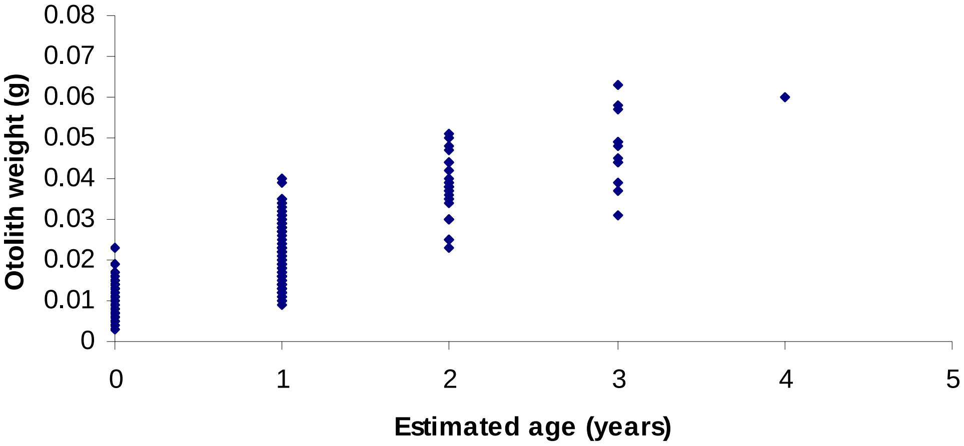


Figure 10. The relationship between estimated fish age and otolith weight for *N. aurifilum*.

DISCUSSION

This study indicates that *N. theodorei and N. aurifilum* are a relatively short-lived species. Ages are an estimate only and are un-validated for this species. Incremental structure and morphological characteristics were similar for both species. One of the major difficulties with ageing these species from thin otolith sections was determining the position of the first increment. The distance between the primordium and the first increment varied considerably between individual samples. For some preparations, the distance to the first increment was similar to the position of the second increment in other specimens. Assuming that increment formation occurs over a short time period (approximately 3 months), the relatively high distance from the first increment may suggest either a broad or multiple spawning period. Analysing the distribution between month of capture and otolith weight (Figure 3 and Figure 8) also supports this hypothesis. The distribution of fish with small otoliths (<0.01g, 0+ age class) extends over several months.

The distribution between otolith weight and age was relatively linear for both species. This suggests that unlike fish length, otoliths continue to grow as the fish age. Although a linear relationship clearly existed, the approximate otolith weight at each age class varied between species. *Nemipterus theodorei* exhibited a higher otolith mass growth rate compared to *N. aurifilum*.

The index of average per cent error (IAPE) was 3.6% and 5.06% and the average readability score was 2.22 and 2.4 for *N. theodorei and N. aurifilum* respectively. The otolith structure of *N. aurifuilum* was considered to be more complex than *N.theodori*. This was reflected in the higher IAPE and higher average readability score. Age difference plots and frequency distributions indicated that there was little evidence of a bias to over or under-estimate age for both these species.

REFERENCES

Anderson, J.R., Morison, A.K., and Ray, D.J. (1992). Age and growth of Murray cod, *Maccullochella peelii* (Perciformes: Percichthyidae), in the lower Murray-Darling Basin, Australia, from thin-sectioned otoliths. In ‘Age Determination and Growth of Fish and Other Aquatic Animals’. (Ed. D.C. Smith.) *Australian Journal of Marine and Freshwater Research* 43: 983-1013.

Beamish, R., and Fournier, D.A. (1981). A method for comparing the precision of a set of age determinations. *Journal of the Fisheries Research Board of Canada* 36: 1395-1400.

Efron, B., and Tibshirani, R.J. (1993). An Introduction to the Bootstrap. *Chapman and Hall, New York.* 436 pp.

Francis, R. I. C. C., L. J. Paul, and K. P. Mulligan, (1992). Ageing of adult snapper (*Pagrus auratus*) from otolith annual ring counts: validation by tagging and oxytetracycline injection. Pages 1069-1089 in: D. C. Smith, editor Age Determination And Growth In Fish And Other Aquatic Animals. Australian Journal of Marine and Freshwater Research 43.

Morison, A.K., Robertson, S.G., and Smith, D.C. (1998). An integrated production fish ageing system: quality assurance and image analysis. *North American Journal of Fisheries Management* 18: 587-5

Rao, D.M. and Rao, K.S. (1986) Studies on the age determination and growth of *Nemipterus japonicus* (Bloch) of Visakhapatnam. Indian Journal of Fish. Vol 33 (4), p 426.