

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

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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), (b) a radial escape section bycatch reduction device (BRD) and (c) both devices together, on bycatch and prawn catch rates in the Queensland shallow water eastern king prawn (*Penaeus plebejus*) trawl fishery. The bycatch was comprised of 250 taxa, mainly gurnards, whiting, lizard fish, 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 kg/hectare (ha^{-1}) (S.E. 0.90) swept by the trawl gear and 0.94 kg ha^{-1} , respectively. For the range of depths sampled (20.1–90.7 m), bycatch 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, the bycatch rate declined by 24% 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 rates are promising, particularly for *S. robusta*, which is targeted in another fishery. Prawn trawl operators are not permitted to retain *S. robusta* and the devices examined herein offer the potential to significantly reduce the incidental fishing mortality that this species experiences. © 2006 Elsevier B.V. All rights reserved.

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1. 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) and 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

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of vessels. In 2004 the fishery consisted of approximately 490 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 targets penaeid prawns (*Penaeus* spp. and *Metapenaeus* spp.) and saucer scallops (*Amusium ballotti*), but fishers are also permitted to retain limited amounts of other marketable species including octopus (*Octopus* spp.), mantis shrimps (Stomatopoda) and cuttlefish (*Sepia* spp.), which are collectively referred to as by-product. 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 occurs 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 fin fish 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) was developed by Watson and Taylor (1988) and 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. This is a major sector of the Queensland east coast trawl fishery and small pelagic finfish are known to comprise a large component of its bycatch. Specifically, the 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. The effects of the devices on the catch rates and size of individual bycatch species were also examined, as well the faunal community composition. The study was part of a larger research project that was designed to provide quantitative advice to the fishery's managers on the effectiveness of BRDs.

2. Materials and methods

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. The charter was designed to reflect the trawling methods, locations and bycatch of the commercial fishery as much as practically pos-

sible. 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.

2.1. Spatial distribution of sampling

Trawling commenced each night about 30 min after sunset. Each trawl took approximately 53 min 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 $\times$ 6 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 5-year period (1995–1999) for each of the logbook's 6 min $\times$ 6 min 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.

2.2. 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 (Fig. 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 (Fig. 1A–C). A hoop constructed from plastic-coated steel wire rope with a diameter of 14 mm was attached to 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

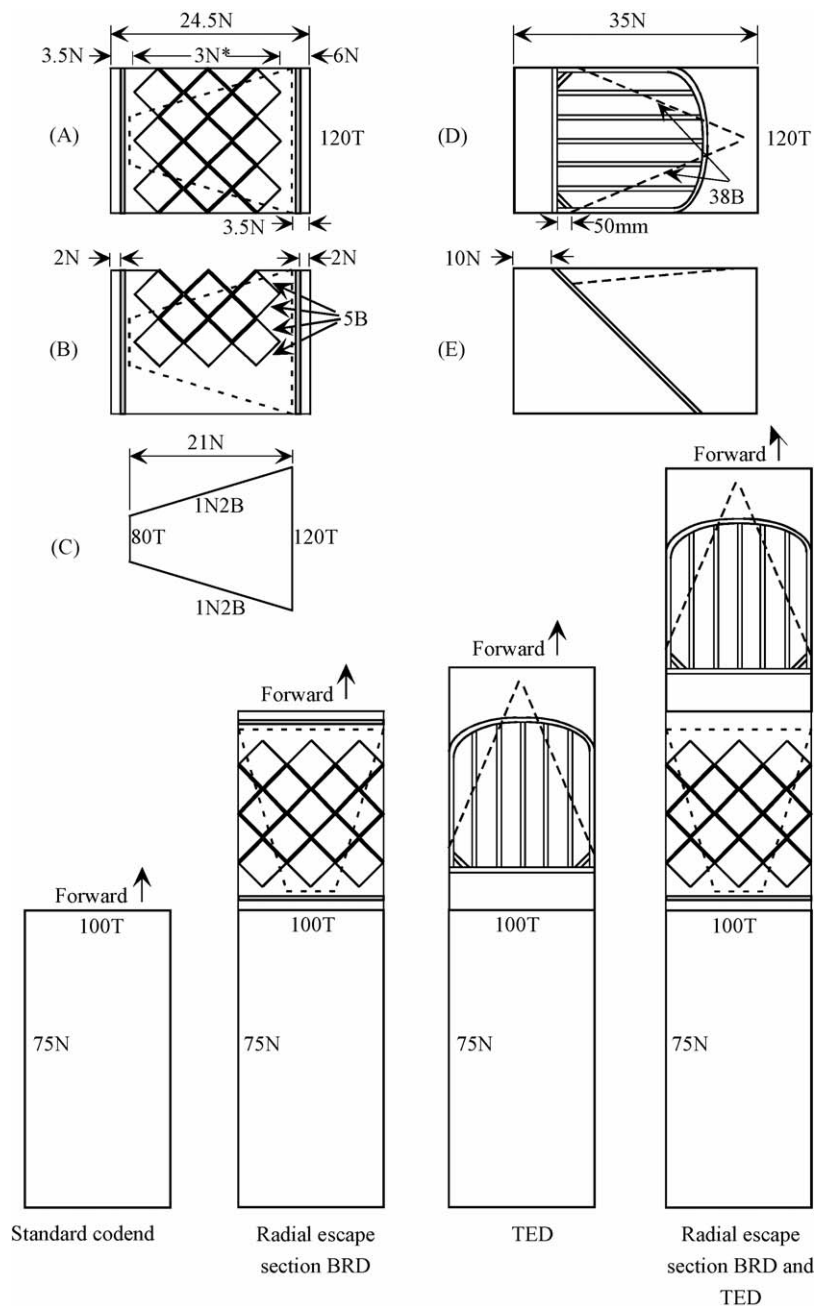


Fig. 1. Design of the radial escape section BRD, TED and the four net treatments used in the charter. (A) Plan (or top) view of the radial escape section BRD. (B) Elevation (or side) view of the radial escape section BRD. (C) Plan (or top) view of the funnel used in the radial escape section BRD (note that the same view is obtained from the side). (D) Plan (or top) view of the modified Wick's TED. (E) Elevation (or side) view of the modified Wick's TED. Lower diagrams show plan (top) views of 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 asterisk (*), which was hand-sewn and is approximately 200 mm. T and N refer to transverse and normal meshes, respectively.

braided polyethylene and equated to 200 mm mesh. The panel of large mesh was 12 meshes wide $\times$ 3 meshes deep.

The standard codend (Fig. 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 Wicks TED (Fig. 1D and 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° 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.

Table 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

2.3. 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 latter processing in the laboratory. By-product 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). Prawns 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 allocated to a species pile that was weighed and recorded. The precise total weight of each sub-sample was determined by summing the individual species weights contained within it. 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) in each sub-sample were obtained from a maximum of 20 individuals selected randomly from each species pile.

2.4. 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:

$$S_{tn} = \frac{HFD}{10,000}$$

where H was the headline length of the net (12.8 m), F 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 from m^2 to ha. Because the weight of individual bycatch species was not directly measured (i.e. the bycatch was sub-sampled) it was extrapolated using the following:

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

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

2.5. Statistical design and analyses

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 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 remov-

Table 2

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 $\times$ 2 nets)

Response variable	Mean observed catch rate in kg ha ⁻¹ (S.E.) Standard net	Parameter estimates (S.E.) (proportionally scaled to a standard net parameter value of 1)			Distribution type
		TED only	Radial escape section BRD only	Radial escape section BRD +TED	
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)

Generalised linear modelling was used to quantify codend treatment effects. Significant effects ($P < 0.05$) are bolded. Treatments with the same alphabetic character (A, B, C or D) were not significantly different. Parameter estimates were proportionally scaled so they can be compared to a standard net parameter value of 1.

ing the codends and sewing on new ones took about 20 min 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.

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:

$$U = \beta_0 + \beta_1(\text{trawl location}_{1-60}) + \beta_2(\text{side of vessel}_{1-2}) + \beta_3(\text{codend type}_{1-4}) + \varepsilon$$

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, β_0 and β_2 were scalar parameters that were estimated, and β_1 and β_3 were the vector parameters that were estimated and ε was the error term. Only estimates of β_3 are presented as this parameter quantifies the effects of the different codend types. For purposes of interpretation, the β_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 β_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°. 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.

3. Results

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

3.1. 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 loca-

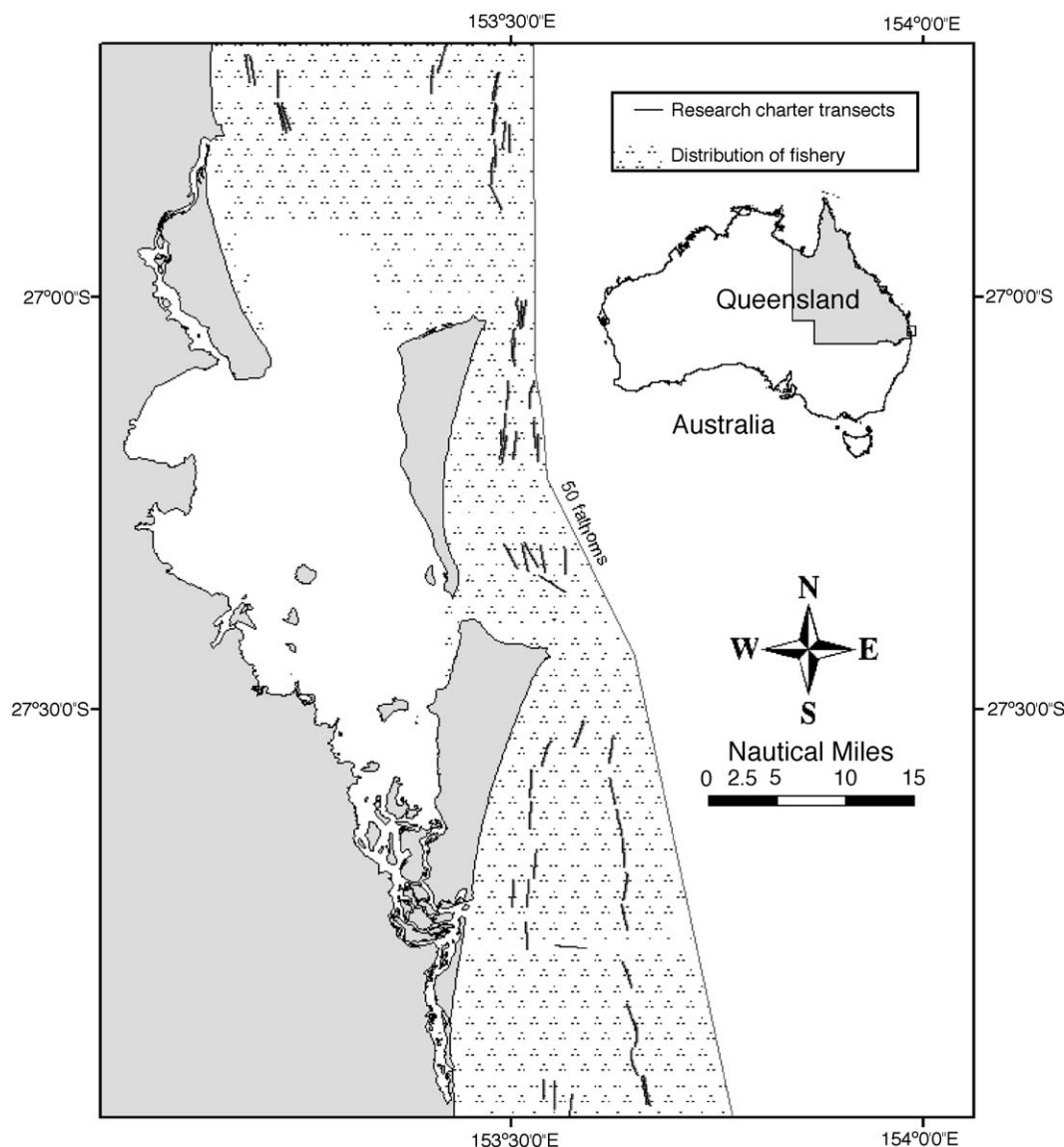


Fig. 2. Location of the 60 two-nautical mile trawl sites in the shallow water eastern king prawn fishery that were sampled during the experimental research charter. Measures of prawn catches, bycatch and bycatch sub-samples were obtained from two nets (port and starboard) towed simultaneously at each location. Each “transect” is comprised of approximately 50 location data point readings taken directly from the vessel’s global positioning system at 1 min intervals while trawling and imported into a geographic information mapping program (ArcVIEW) for presentation.

tions (Fig. 2) (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 kg ha^{-1} (S.E. 0.44) for bycatch and 0.98 kg ha^{-1} (S.E. 0.09) for prawns. The depth of the trawls ranged between 20.1 and 90.7 m, with most between 40.0 and 90.0 m. There was no significant effect of depth on prawn catch rates, however bycatch rates declined significantly ($P < 0.01$) at a rate of 0.14 kg ha^{-1} for every 1 m increase in depth (Fig. 3).

The observed mean catch rate of bycatch from the standard net was 11.06 kg ha^{-1} (S.E. 0.90) (Table 2). All codend treatment types significantly ($P < 0.05$) reduced bycatch 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% (β_3 parameter estimate of 0.76, Table 2), while the radial escape section by itself resulted in a reduction of 19% (β_3 parameter estimate of 0.81) and the TED by itself a reduction of 10% (β_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*

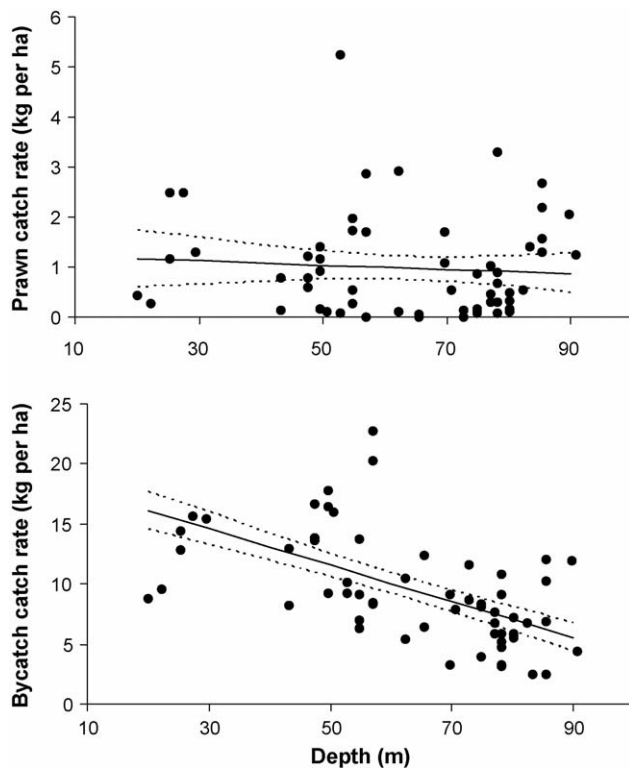


Fig. 3. The effect of depth on catch rates of prawns and bycatch in the Queensland shallow water eastern king prawn trawl fishery, based on 120 measurements from the experimental research charter. Dotted lines are 95% confidence intervals of the mean.

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 2). There was a significant reduction of 20% ($P < 0.05$, β_3 parameter estimate of 0.80, Table 2) in the net with both radial escape section BRD and TED. Most of the prawn loss was attributed to the TED ($P < 0.05$, β_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* ($2126.23 \text{ g ha}^{-1}$), stout whiting *Sillago robusta* (780.81 g ha^{-1}), lizard fish *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 concatenes* (169.29 g ha^{-1}), the spot-tail wide-eye flounder *Engyproso-*

pon grandisquama (167.94 g ha^{-1}) and the slender flounder *Pseudorhombus tenuirastrum* (152.9 g ha^{-1}). No turtles were encountered during the charter.

The codend effects were examined for 24 species that comprised 90% of the total bycatch weight from the standard net (Table 3). 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 *P. rubromarginatus* (90% of samples), the lizard fish *S. grandisquamis* (83% of samples) and the triangular box-fish *T. concatenes* (76% of samples). Catch rates for *L. argus* ($2698.03 \text{ g ha}^{-1}$) were more than twice that of any other species. Of the 24 species, 18 displayed lower predicted catch rates 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 *T. 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 3). The largest reduction was achieved for *S. robusta* where catch rates fell 57% from $1,275.12 \text{ g ha}^{-1}$ 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 3).

The effects on the mean length of bycatch species were variable. Fifteen of the 24 species examined above were unaffected, while the mean lengths of nine species were significantly affected by one or both devices (Table 4). The flathead *R. 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 *M. 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 lizard fish *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 *Upeneus asymmetricus* also increased, but mainly due to the BRD.

3.2. 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 (Fig. 4A–C). ANOSIM revealed that bycatch assemblages differed significantly between depths (global $R = 0.563$, $P < 0.001$), with

Table 3

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

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

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. Standard errors (S.E.) are in parentheses. The parameter estimates have been proportionally scaled so they can be compared to a Standard net parameter value of 1.

Table 4
Effects of the TED and radial escape section BRD on bycatch species' lengths

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

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 (S.E.) of predicted means are in parentheses.

the largest differences between the shallowest and deepest categories. Pairwise tests for the (a) 20 and 70 m groups, (b) 20 and 80 m groups, (c) 20 and 90 m groups and (d) 30 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°S) and southernmost (28°S) sites (R -statistic = 0.734, Fig. 4B). 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 *P. 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 (Fig. 4C).

4. Discussion

4.1. Evaluating the performance of the TED and radial escape section BRD

Our study has shown that bycatch can be significantly reduced (β_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 (β_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 fin fish 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

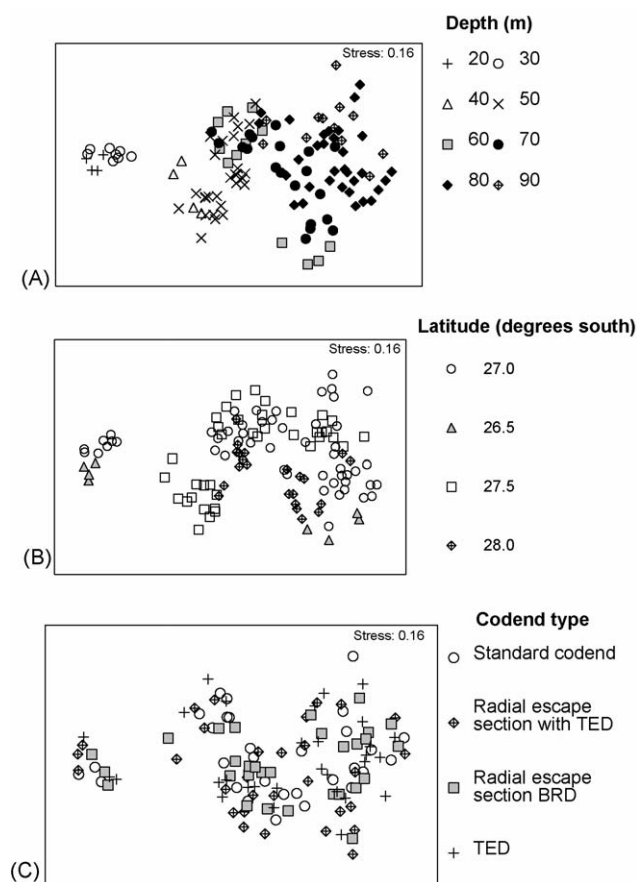


Fig. 4. Two-dimensional MDS of bycatch sub-samples from an experimental research charter undertaken in the Queensland shallow water eastern king prawn trawl fishery. Catch rates were square-root transformed. The analyses used all 120 sub-samples and 118 species. Factors examined were (A) depth, (B) latitude and (C) codend type.

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 the present 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 3). However the largest reductions, which were achieved for the stout whiting *S.*

robusta (57% reduction) and the scad *T. novaezelandiae* (32% reduction), were attributed mainly to the radial escape section. Both of these species are benthic-pelagic with fusiform body shape and a reasonably strong swimming ability. Length analyses (Table 4) 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 (Fig. 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 4). 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 et al. (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.

4.2. 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 fin fish and crabs, mainly gurnards, stout whiting, portunid crabs, lizard fish, flatheads, dragonets and flounders, and (c) faunal community assemblages that were affected by depth (20–90 m) and latitude (25–28°S). When results from the single species (Table 3) and multivariate (Fig. 4) 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 (18–19°S). They sampled eight sites on a monthly basis for 2 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 (10–15°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 (29–33°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.

4.3. 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 kg ha⁻¹ (S.E. 0.90) for bycatch and 0.94 kg ha⁻¹ (S.E. 0.16) for prawns, or 11.78 kg bycatch/kg (S.E. 2.19) of prawns. Logbook data show that the average annual reported harvest from the shallow water (<50 m) eastern king prawn fishery from 1988 to 1999 inclusive was about 929.6 t (S.E. 39.5), which using simple extrapolation, equates to an average annual bycatch of 10,948.8 t (S.E. 2085.2). If trawler operators adopted the TED and radial escape section BRD and the 24% reduction in bycatch (Table 2) 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. These estimates of total bycatch are inexact and only provided with the intention of providing the reader some understanding of the approximate absolute reductions in bycatch that could be achieved. 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 2-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 by-product). These estimates equate to prawn-to-total bycatch ratios of 10.4:1 and prawn-to-discarded bycatch (with by-product 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.

Further significant reductions in bycatch rates may be achievable by restricting the depths where trawling can take place. Our results indicate that, for the range of depths sampled (20.1–90.7 m), bycatch rates declined by about 1.4 kg ha⁻¹ for every 10 m increase in depth (Fig. 3). If, for example, the minimum depth at which trawling is permitted was increased from about 20–50 m, the overall mean bycatch rate of 9.56 kg ha⁻¹ observed herein would decline to about 5.36 kg ha⁻¹, which equates to a 44% reduction. While the prawn catch rates were independent of depth, the size and age of the prawns generally increase with depth (Garcia and Le Reste, 1981), and therefore any shift in effort towards deeper grounds is likely to alter the mean size and age of the prawns caught, and therefore affect the yield. Similarly, the shift in effort to deeper waters would also affect the composition of the bycatch (Fig. 4A).

5. Conclusion

The main finding from the study was that when used together, the TED and radial escape section BRD reduced total bycatch rates by 24%, but at the cost of a 20% reduction in the marketable prawn catch rate, compared to a standard net with no TED or BRD (Table 2). 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 benthic-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.

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