Abstract.–In response to recent voluntary adoption of square-mesh codends by commercial prawn trawlers in Gulf St. Vincent, Australia, two new designs of composite square-mesh codends were investigated for their utility in 1) reducing the bycatch of fish and 2) improving size-selectivity of the targeted prawns. The two designs (termed the composite-square-2 and the composite-square-3 codends) comprised mainly large sections of 52-mm netting hung on the bar but had different hanging ratios, tapers, and small diamond-mesh sections. A strategically located panel of 85-mm netting was inserted on the bar into the tops of the anterior sections of each codend to allow small fish to escape. Simultaneous comparisons with a conventional diamond-mesh codend (control) showed that both square-mesh designs significantly reduced the incidental capture of commercially important fish (by up to 96.9%). The numbers of prawns (*Penaeus latisulcatus*) were significantly reduced in both composite square-mesh codends (by up to 12.1%) but there was no significant reduction in weights of prawns. There were no significant differences in the selectivity parameters for prawns between the two designs. The results are discussed in terms of the probable effects that the different square-mesh configurations had on escape of fish and size-selectivity of prawns.

Use and success of composite square-mesh codends in reducing bycatch and in improving size-selectivity of prawns in Gulf St. Vincent, South Australia

Matt K. Broadhurst
South Australian Aquatic Sciences Centre
P.O. Box 120
Henley Beach, South Australia 5022, Australia
Present address: Universidade Federal Rural de Pernambuco-UFRPE
Departamento de Pesca
Laboratório de Oceanografia Pesqueira
Av. Dom Manuel de Mederios
S/n, Dois Irmãos, Recife-PE, Brazil, CEP:52.171-900
E-mail address: fhvhazin@truenet.com.br

Roger B. Larsen
University of Tromsø
Breivika, N-9037, Tromsø, Norway

Steven J. Kennelly
N.S.W. Fisheries Research Institute
P.O. Box 21
Cronulla, New South Wales 2230, Australia

Paul E. McShane
South Australian Aquatic Sciences Centre
P.O. Box 120
Henley Beach, South Australia 5022, Australia

Traditionally configured prawn trawls contain small diamond-shaped meshes in the codend and are not particularly selective fishing gears. In addition to the targeted prawns, they often retain large quantities of nontarget organisms, collectively termed bycatch (for reviews see Andrew and Pepperell, 1992; Alverson et al., 1994). In many prawn-trawl fisheries, this bycatch consists of a diverse assemblage of small fish, cephalopods, and crustaceans, including prawns smaller than optimal commercial size. The mortality of large quantities of juveniles of commercially or recreationally important species, or both, is of major concern, because it may deleteriously affect the recruitment and biomass of stocks targeted by other fisheries. Regulating selectivity of trawls to the desired size of prawns at first capture will also help to optimize yield and maintain sustainability of prawn stocks.

During the past decade, many studies have attempted to improve selectivity of prawn-trawl fisheries by altering the codends of trawls. Most of these studies can be categorized into examinations of 1) bycatch reducing devices (BRDs) that facilitate the escape of unwanted fish (e.g. Watson et al., 1986; Broadhurst and Kennelly, 1997; Rogers et al., 1997); or 2) different sizes, shapes, and configurations of mesh that improve selectivity of the targeted species by reducing the bycatch of conspecifics (e.g. Karlsen

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and Larsen, 1989; Tokai et al., 1990; Thorsteinsson, 1992; Tokai and Sakaji, 1993). However, to minimize biological impacts on bycatch and to promote ecologically sustainable fisheries, prawn trawls should be modified to address both these issues. Furthermore, it is essential that the prawn industry actively contributes towards the development of such designs so that they will be more readily accepted and adopted as part of commercial operations (Kennelly and Broadhurst, 1995).

In some prawn-trawl fisheries, industry has resisted gear modifications because of negative effects on gear performance (e.g. Renaud et al., 1993; Robins-Troeger et al., 1995). However, an inexpensive and simple modification that has been successfully tested and adopted in fish trawls in the North Atlantic involves changing only the configuration of mesh in the codend by hanging conventional diamond-shaped mesh on the bar (termed “square mesh”) (e.g. Robertson and Stewart, 1988; Fonteyne and M’Rabet, 1992; Suuronen and Millar, 1992). Panels of square mesh have also been used successfully in prawn trawls to improve target-selectivity and to reduce the bycatch of juvenile fish. For example, in the Icelandic shrimp, *Pandalus borealis*, fishery, Thorsteinsson (1992) found that codends made entirely from square mesh effectively reduced the catches of small prawns (10–20% of catch) and 0-group gadoids. In New South Wales (NSW), Australia, Broadhurst and Kennelly (1996; 1997) showed that strategically located composite panels of square mesh (BRDs) in diamond-mesh codends effectively excluded large quantities of unwanted fish and there was no concomitant reduction in catches of the targeted prawns, *Penaeus plebejus*.

Through industry involvement in research, these sorts of results have facilitated the rapid endorsement and acceptance of designs in the respective fisheries and in some cases, in other fisheries sharing similar characteristics (e.g. similar gear configurations, target species, etc). An example of this type of transfer of technology recently occurred in the Gulf St. Vincent prawn-trawl fishery in South Australia. This fishery currently involves ten vessels targeting western king prawns, *Penaeus latisulcatus*; some legally retained bycatch comprising balmain bugs, *Ibacus* spp., and southern calamari, *Sepioteuthis australis* are also taken. Operators are restricted by means of a series of controls that include a minimum mesh opening of 45 mm in the codend and a limit of 34 nights of trawling each year. Although no formal studies have been undertaken to determine the selectivity of the conventional gear or to quantify bycatches, in recent years fishermen have suggested that the mesh size is too small and retains unacceptable proportions of juvenile prawns and fish. During the 1996–97 season, in an attempt to increase the mean sizes of prawns caught, fishermen designed and incorporated full square-mesh codends in all their trawls (see Fig. 1).

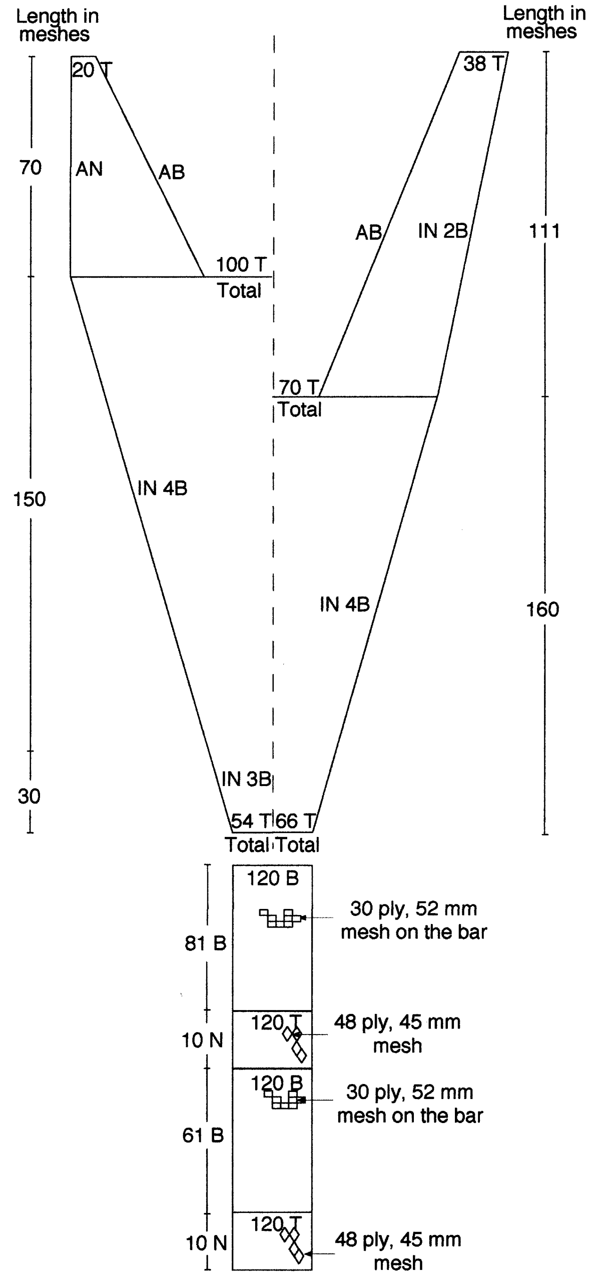

Figure 1

Diagrammatic representation of a “Gundry prawn trawl” and the industry developed “square-mesh-1 codend”. T = transversals; N = normals; and B = bars.

Anecdotal reports from industry suggested that this codend (termed the “square-mesh-1 codend”) reduced the bycatch of juvenile prawns and some small fish, although there were some concerns over suitable configurations of square mesh. Given that industry had already adopted the concept of using square mesh in codends, our aims in the present study were to modify the square-mesh-1 codend, after consultation with industry, so that it 1) incorporated a suitable BRD for unwanted fish and 2) increased the size-selectivity of targeted prawns.

Materials and methods

This study was done on commercial prawn-trawl grounds in Gulf St. Vincent, South Australia (Fig. 2), in November 1997, with a chartered commercial prawn-trawler (15 m). Three locally used prawn trawls (termed "Gundry trawls," Fig. 1), each with a headline length of 9.14 m were rigged in a standard triple gear configuration (see Andrew et al., 1991) and towed at 3 knots across a combination of sandy and light coral bottoms at depths ranging from 12 to 16.5 m. Each of the two outside trawls were rigged with zippers (Buraschi S-146R, pinlock sliders) to facilitate codend changes. The lengths of these zippers were calculated by assuming a fractional mesh opening of 0.35 (Broadhurst and Larsen, personal obs.) × the stretched mesh length × the mesh circumference. The middle net was not rigged in an identical manner to the outside trawls and therefore was excluded from any analysis.

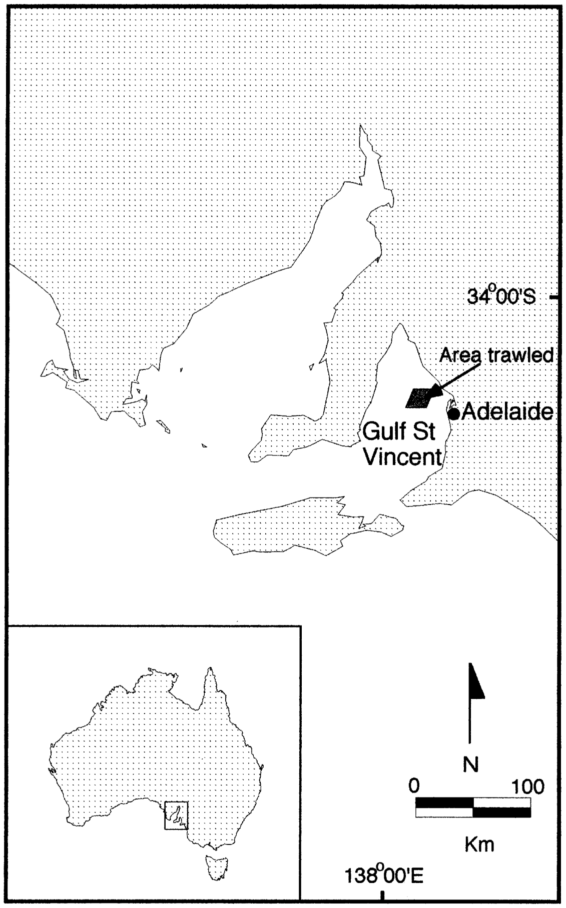

Figure 2

Location of Gulf St. Vincent and the area trawled.

Codends examined

Three codends, each attached to a zipper, were used in the experiment. The first codend, termed the control (Fig. 3A), represented conventional codends used prior to the 1996–97 fishing season and was made entirely of diamond-shaped meshes (45-mm mesh size, 2.35-mm diameter, 24-strand polyethylene twine), measuring 81 meshes in length and 100 meshes in circumference. The second and third codends (termed the composite-square-2 and composite-square-3 codends) comprised two sections of 52-mm mesh (400/36 ply, UV-stabilized, high-density polyethylene twine) cut on the bar. Each square-mesh section consisted of an upper and lower panel, sewn together so that knot directions were opposite. A panel of 85-mm netting (3-mm braided polyethylene twine), measuring 6 bars × 11 bars, was inserted into the tops of the posterior sections of each square-mesh codend starting approximately 1.1 m anterior to the last row of meshes (Fig. 3, B and C). This panel was positioned in a manner similar to that for the composite square-mesh panel used in NSW oceanic prawn trawls (see Broadhurst and Kennelly, 1996; 1997): that is, in an area of maximum displacement of water anterior to the end of the codend (to facilitate the escape of small fish, Broadhurst et al., 1999) but sufficiently in front of the anticipated build-up of catch.

The composite-square-2 codend comprised anterior and posterior square-mesh sections measuring 55 bars and 61 bars in length respectively. This codend was similar to the industry-developed square-mesh-1 codend, except that it had a circumference of 62 bars (1.6 m). The reduction in circumference from 120 bars (i.e. the industry design) to 62 bars was based on the expected fishing circumference of the normal diamond-mesh codend: that is, a fractional mesh opening (0.35) × the mesh size (45 mm) × the mesh circumference (100 T) = approx. 1.6 m. Two diamond-mesh 45-mm sections (mesh size, 400/48 ply UV-stabilized, high-density polyethylene twine), 10 meshes in length, and 100 meshes in circumference were inserted between the two square-mesh sections and immediately aft of the posterior square-mesh section (hanging ratio of 0.36) (Fig. 3B). The ante-

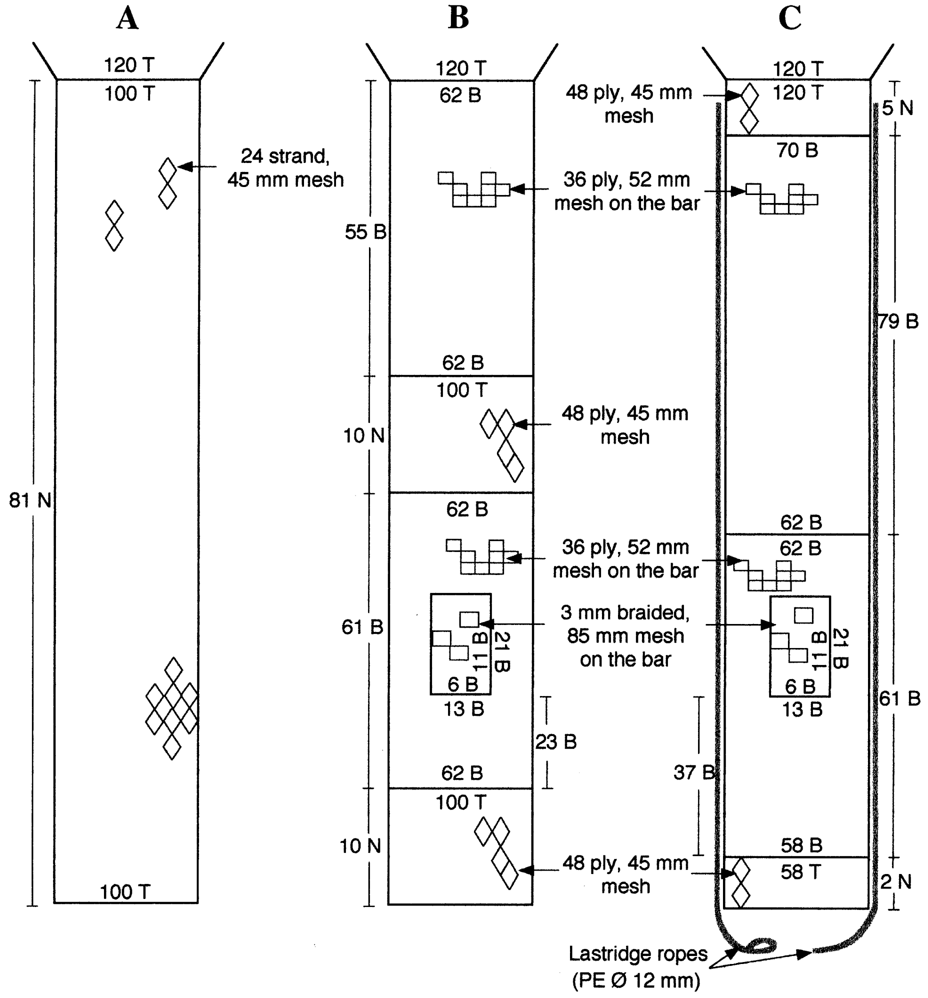

Figure 3

Diagrammatic representation of (**A**) the control codend, (**B**) composite-square-2 codend, and (**C**) composite-square-3 codend. T = transversals; N = normals; and B = bars.

rior diamond-mesh section was used to attach the codend lifting rope (termed "lazy-line"), whereas the posterior diamond-mesh section was used to attach the draw-string of the codend.

The composite-square-3 codend comprised an anterior square-mesh section 79 bars in length attached to a posterior square-mesh section 61 bars in length (Fig. 3C). The circumference of this codend tapered from 70 bars at the start of the anterior section to 58 bars at the end of posterior section. Two diamond-mesh sections (400/48 ply mesh size, UV-stabilized, high-density polyethylene twine), 2 meshes in length were attached immediately anterior and posterior (hanging ratio of 0.57) to the two square-mesh sections (Fig. 3C). The anterior diamond-mesh section measured 120 meshes in circumference, whereas the posterior diamond-mesh section measured 58 meshes in circumference and had the codend draw-string attached. Two 4.5-m lengths of 12-mm diameter, 3-strand polyethylene rope (termed "lastridge ropes") were firmly laced at a hanging ratio of approx. 0.9 to each of the two seams of the composite-square-3 codend to provide additional lengthwise strength to the entire codend. The posterior ends of the lastridge ropes extended past the codend and were secured together during each tow.

Sampling protocol and data collected

The two composite square-mesh codends were separately compared against the control codend. In each paired comparison, the control and composite square-mesh codend being tested were zipped to each outside trawl of the triple-rigged gear and towed simultaneously. The codends were used in normal commercial tows of 45-min duration and randomly assigned after each tow (to eliminate biases between different trawls and sides of the vessel). The location of each tow was randomly selected from the available prawn-trawl locations that were possible under the fishing conditions. Over a total period of five nights, we initially completed 11 replicate tows of the composite-square-2 codend against the control. On the basis of results of this comparison and after discussions with representatives of industry, we then designed and constructed the composite-square-3 codend and immediately tested it against the control over another 11 replicate tows.

After each tow, the two codends were emptied onto a partitioned tray. Prawns and all individuals of commercially important species comprising bycatch were separated by species. The following categories of data were selected for each tow: the total weight of prawns and a subsample (100 prawns from each codend) of their lengths (to the nearest 1-mm carapace length); the total number of prawns (estimated from the weight of the subsample); the weights of total discarded bycatch, discarded noncommercial bycatch (i.e. species of no commercial value), and retained bycatch; the weights and numbers of commercially or recreationally (or both) important bycatch species; and the sizes (to the nearest 0.5 cm) of commercially or recreationally (or both) important fish. A random sample of prawns (approx. 14 kg) from each codend in each tow was separated and sent to A. Raptis & Sons PTY LTD (seafood processing plant) in Hindmarsh, Adelaide, where they were graded into commercial categories (number per pound) by a locally built automated "dynamic grading machine."

Several commercially important species were caught in sufficient quantities to enable meaningful comparisons. These were western king prawns, sand trevally, *Pseudocaranx wrighti*, red mullet, *Upeneichthys porosus*, school whiting, *Sillago bassensis*, Degen's leatherjacket, *Thamnaconus degeni*, southern sand flathead, *Platycephalus bassensis*, cuttlefish, *Sepia* spp., small-toothed flounder, *Pseudorhombus jenynsii*, and southern calamari.

Analysis of catch data

Data for all replicates that had sufficient numbers of each variable (defined as >2 individuals in at least 8 replicates) were analyzed with paired *t*-tests ($P \leq 0.05$). Except for the weights and numbers of prawns and small-toothed flounder, all variables were analyzed by using one-tailed tests of the hypothesis that the square-mesh codends caught less than the control. Although the composite square-mesh codends might have been expected to retain fewer prawns than the conventional diamond-mesh control codend (due to the larger square-shaped mesh), Broadhurst and Kennelly (1996; 1997) showed that trawls fitted with composite square-mesh panels caught more prawns than conventional trawls (possibly owing to a reduction in drag and a corresponding increase in swept area). Therefore, the weight and number of prawns were analyzed by using two-tailed tests. Catches of small-toothed flounder, a species that cannot pass through the square meshes, were also compared by using two-tailed tests. With the exception of data for catches of prawns, where analyses provided similar results for weights and numbers of variables, only data concerning numbers were included in Figure 4 to conserve space.

Size frequencies of commercially or recreationally (or both) important fish were plotted and compared with two-sample Kolmogorov-Smirnov tests ($P=0.05$), where there were sufficient data ($n>25$ in each codend, pooled across all tows).

Analysis of size-selectivity of prawns

The relatively large size of mesh used in the control (45-mm diamond mesh), compared with the composite square-mesh codends (52-mm mesh on the bar), meant that their selectivities overlapped. Insufficient numbers of smaller prawns were retained among individual hauls to enable analyses of between-haul variation (see Fryer, 1991). To provide sufficient data for analyses, size frequencies of prawns from each codend were combined across all tows. An estimated split model (Millar and Walsh, 1992) was used to fit logistic selection curves to these data by maximum likelihood method (Pope et al., 1975) by using the program "CC Selectivity" (Wileman et al., 1996). Logistic curve parameters, their standard errors, and 95% confidence limits were calculated for each codend. For each logistic curve, model deviance values were determined for a goodness-of-fit hypothesis (i.e. to test H_0: that the curves were logistic).

Size categories of commercially graded prawns from each codend were plotted and analyzed by using two-sample Kolmogorov-Smirnov tests ($P=0.05$). In these analyses, the numbers of prawns pooled across all samples from each codend were used for the degrees of freedom.

Results

Analysis of catch data

Compared with the control codend, both the composite-square-2 and composite-square-3 codends significantly reduced the numbers of prawns caught (means reduced by 8.7% and 12.1%, respectively), with no significant reduction in weights (although the means were reduced by 1.8% and 3.7%, Fig. 4, A–B; Table 1). The weights of total discarded bycatch and discarded noncommercial bycatch were significantly reduced by 67.7% and 69.0%, respectively, in the composite-square-2 codend, whereas the composite-square-3 codend reduced these amounts by 58.4% and 54.2%. respectively (Fig. 4, C–D; Table 1). Both composite square-mesh codends significantly reduced the numbers and weights of sand trevally (by between 68.0% and 76.6%), red mullet, (by between 87.2% and 96.9%), school whiting (by between 90.6% and 96.9%), and southern sand flathead (by between 57.0% and 84.9%) (Fig. 4, E–H; Table 1). The composite-square-2 codend significantly reduced the mean number and weight of Degen's leatherjacket caught by 31.8% and 23.4%, respectively, and although not significant, these amounts were reduced by 24.6% and 20.8%, respectively, in the composite-square-3 codend (Fig. 4I; Table 1). There was also a significant reduction in the numbers of retained southern calamari, by 33.9% in the composite-square-3 codend (Fig. 4J; Table 1).

Two-sample Kolmogorov-Smirnov tests comparing the size-frequency distributions for fish measured from the control and composite square-mesh codends showed significant differences in the relative size compositions of sand trevally retained by both composite square-mesh codends and red mullet retained by the composite-square-2 codend (the control codend retained proportionally more larger fish, Fig. 5, A–B). No significant differences were detected in the size compositions of Degen's leather jacket retained in the composite square-mesh and control codends (Fig. 5C). There were insufficient data to analyze size-frequency distributions of school whiting and southern sand flathead.

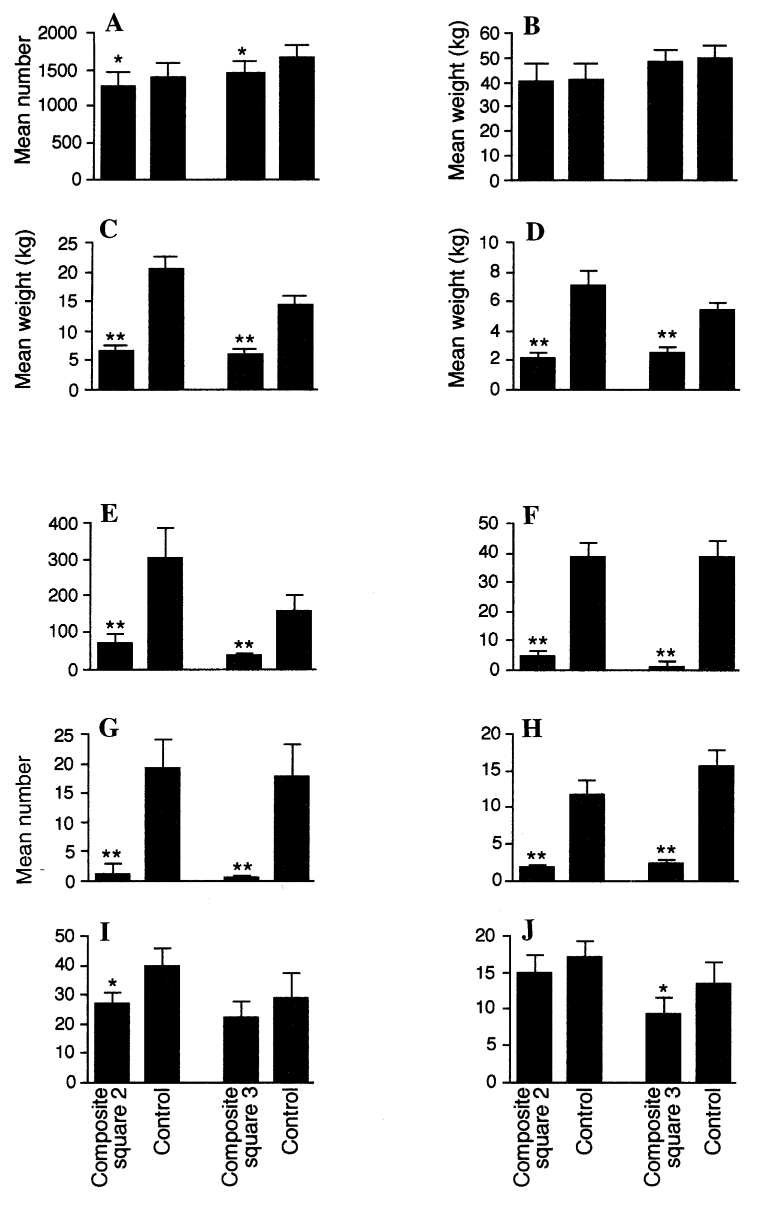

Figure 4

Differences in mean catches (per 45-min tow ± SE) between the composite square-mesh codends and control codend: the (**A**) numbers and (**B**) weights of king prawns (*Penaeus latisulcatus*); the weights of (**C**) total discarded bycatch and (**D**) discarded noncommercial bycatch; and the numbers of (**E**) sand trevally (*Pseudocaranx wrighti*), (**F**) red mullet (*Upeneichthys porosus*), (**G**) school whiting (*Sillago bassensis*), (**H**) southern sand flathead (*Platycephalus bassensis*), (**I**) Degen's leather jacket (*Thamnaconus degeni*), and (**J**) southern calamari (*Sepioteuthis australis*). ** = significant ($P<0.01$); * = significant ($P<0.05$).

Analysis of size-selectivity of prawns

The raw data, observed selectivity, and calculated logit values for prawns captured in the codends are listed in Table 2. Figure 6 shows the corresponding logistic length selection curves derived for each composite square-mesh codend. Model deviance indicated sufficient goodness of fit for both of these selection curves (Table 3; Fig. 7) although some size classes

Table 1

Summaries of paired *t*-tests comparing composite square-mesh and control codends. Weights and numbers of prawns and small-toothed flounder were analyzed with a two-tailed paired *t*-tests, whereas the remaining variables were analyzed with one-tailed paired *t*-tests. *n* = number of replicates; disc = discarded; noncomm = noncommercial. Significant *P*-values are in bold.

	Composite-square-2 versus control			Composite-square-3 versus control		
	Paired *t*-value	*P*	*n*	Paired *t*-value	*P*	*n*
No. of prawns	2.574	**0.027**	11	2.853	**0.017**	11
Wt. of prawns	0.648	0.531	11	0.915	0.382	11
Wt. of total disc bycatch	6.521	**0.0001**	11	6.662	**0.0001**	11
Wt. of disc noncomm bycatch	5.251	**0.0002**	11	6.051	**0.0001**	11
Wt. of retained bycatch	–0.424	0.659	11	0.947	0.183	11
No. of sand trevally	3.345	**0.003**	11	3.719	**0.002**	11
Wt. of sand trevally	4.016	**0.001**	11	4.050	**0.001**	11
No. of red mullet	6.901	**0.0001**	11	6.728	**0.0001**	11
Wt. of red mullet	6.927	**0.0001**	11	8.033	**0.0001**	11
No. of school whiting	6.912	**0.0001**	11	5.111	**0.0003**	10
Wt. of school whiting	4.887	**0.0003**	11	4.896	**0.0004**	10
No. of Degen’s leatherjacket	2.442	**0.017**	11	1.378	0.099	11
Wt. of Degen’s leatherjacket	1.945	**0.040**	11	1.139	0.140	11
No. of southern sand flathead	5.470	**0.0002**	11	6.328	**0.0001**	11
Wt. of southern sand flathead	5.487	**0.0002**	11	3.585	**0.0025**	11
No. of cuttlefish	1.247	0.122	10	1.037	0.163	10
Wt. of cuttlefish	1.217	0.127	10	0.792	0.224	10
No. of small-toothed flounder	–0.882	0.407	8	1.537	0.163	9
Wt. of small-toothed flounder	0.940	0.378	8	0.208	0.779	9
No. of southern calamari	0.772	0.229	11	3.123	**0.005**	11
Wt. of southern calamari	–0.576	0.711	11	–0.179	0.568	11

had high deviance residuals (Fig. 7, see also Appendix). Although all selectivity parameter estimates were slightly greater in the composite-square-3 codend, the 95% confidence limits for these estimates indicated that there were no statistically significant differences between the two modified codends.

Two-sample Kolmogorov-Smirnov tests comparing the commercial size compositions of prawns retained in each codend showed significant differences between the composite square-mesh and control codends (Fig. 8). Both composite square-mesh designs caught proportionally more larger prawns (<9/12 per pound) and fewer smaller individuals (>16/20 per pound).

Discussion

The work described in this paper illustrated the effectiveness of a strategically located panel of square mesh in codends for reducing catches of juvenile fish (see also Robertson and Stewart, 1988; Fonteyne and M’Rabet, 1992; Briggs, 1992; Broadhurst and Kennelly, 1996, 1997) and quantified, for the first time in commercial penaeid prawn-trawls, the utility of large panels of square mesh for improving the size-selectivity of the targeted prawns.

The composite square-mesh codends were equally effective in excluding large quantities of small individuals of fusiform species, including sand trevally, red mullet, school whiting, and southern sand flathead and there was no significant reduction in weights of prawns or total retained bycatch (Fig. 4; Table 1). Although the square mesh used throughout the main sections of both codends may have been large enough to permit some smaller fish (e.g. red mullet) to escape, the differences in the sizes of many fish retained between the composite square-mesh codends and the control (Fig. 5) indicated that to achieve the significant and quite large reductions in catch, most fish probably escaped through the larger 85-mm mesh panel located in the tops of the posterior sections of the codends.

The escape of large numbers of these individuals through the 85-mm square-mesh panel in both codends may be attributed to the influences of water

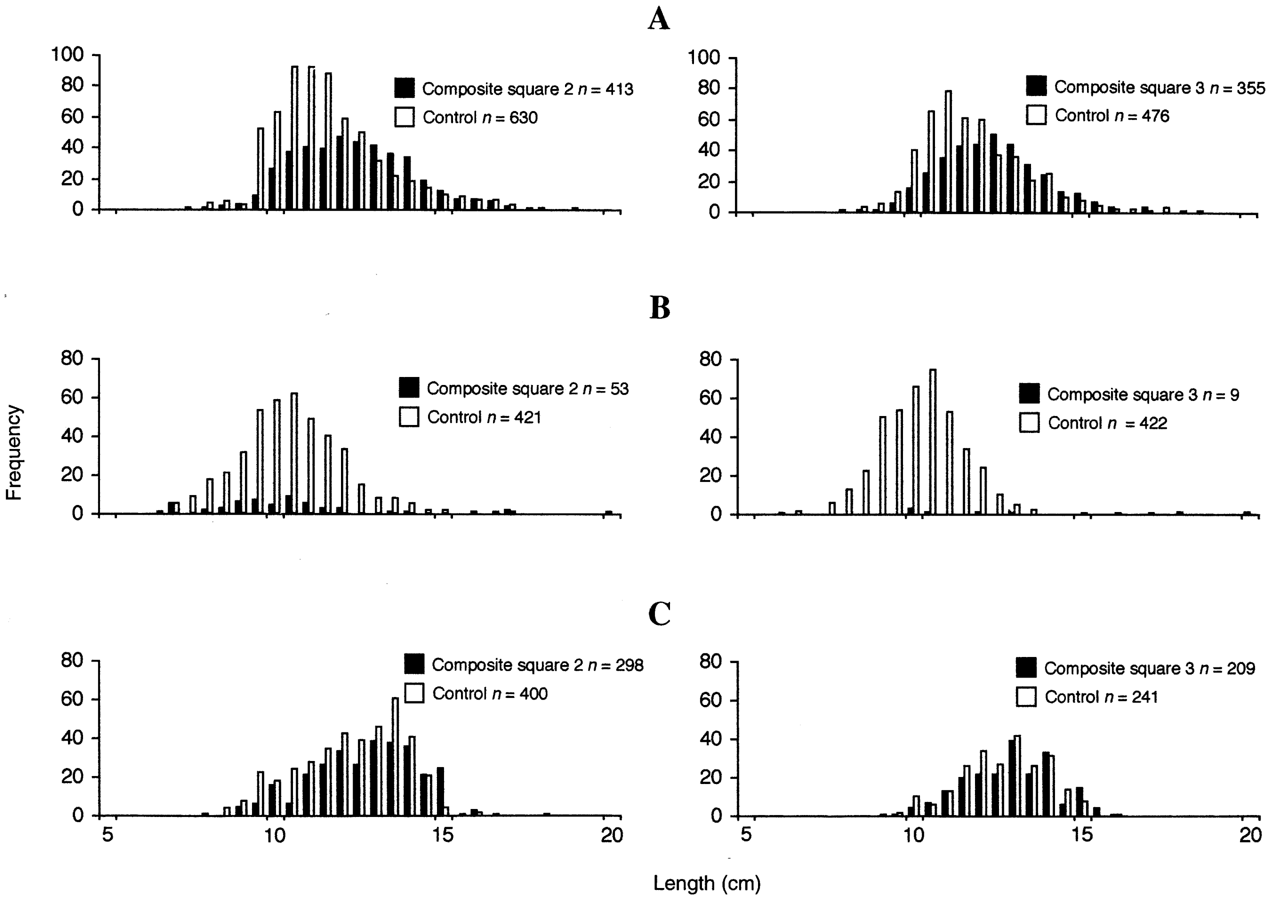

Figure 5

Size-frequency distributions of the composite square-mesh codends and control codend for (**A**) sand trevally (*Pseudocaranx wrighti*), (**B**) red mullet (*Upeneichthys porosus*), (**C**) Degen's leatherjacket (*Thamnaconus degeni*), (**D**) school whiting (*Sillago bassensis*), and (**E**) southern sand flathead (*Platycephalus bassensis*).

flow anterior to the catch. The location of the panel (approx. 1.1 m from the end of the codend, Fig. 3) was based on a similar design (termed the composite square-mesh panel) that is currently used commercially in oceanic prawn trawls in NSW where it has been shown to be very effective in reducing the bycatch of large numbers of small fish (Broadhurst and Kennelly, 1996, 1997). In previous experiments, Broadhurst and Kennelly (1996) and Broadhurst et al. (1999) determined that at this position, there is some displacement of water forwards owing to the twine area and build-up of catch in the posterior section of the codend. Because small fish are probably using anaerobic muscle power to maintain position in the moving trawl and are quite fatigued when they enter the codend, this displaced water may be sufficient 1) to assist them to swim forwards and out through the larger meshes in the panel; and (or) 2) to enable them to reduce their tail-beat frequencies and maintain their position in the vicinity of the larger mesh for a longer period, increasing their chances of randomly escaping. The extent to which such a flow facilitated the escape of fish in the present study probably depended on their relative size or physiology (or both), because these factors largely influence swimming speed and endurance (Beamish, 1978). For example, the bycatch of fast-swimming species, such as sand trevally, and relatively large individuals of school whiting and southern flathead was greatly reduced in the two modified designs. However, although statistically significant, there was only a 30% reduction in the numbers of the relatively small Degen's leather jackets in the composite-square-2 codend and a lower nonsignificant 24% reduction in the composite-square-3 codend (Fig. 4I; Table 1).

A possible explanation for the significant reduction of Degen's leather jacket from the composite-square-2 codend may be the configuration of mesh

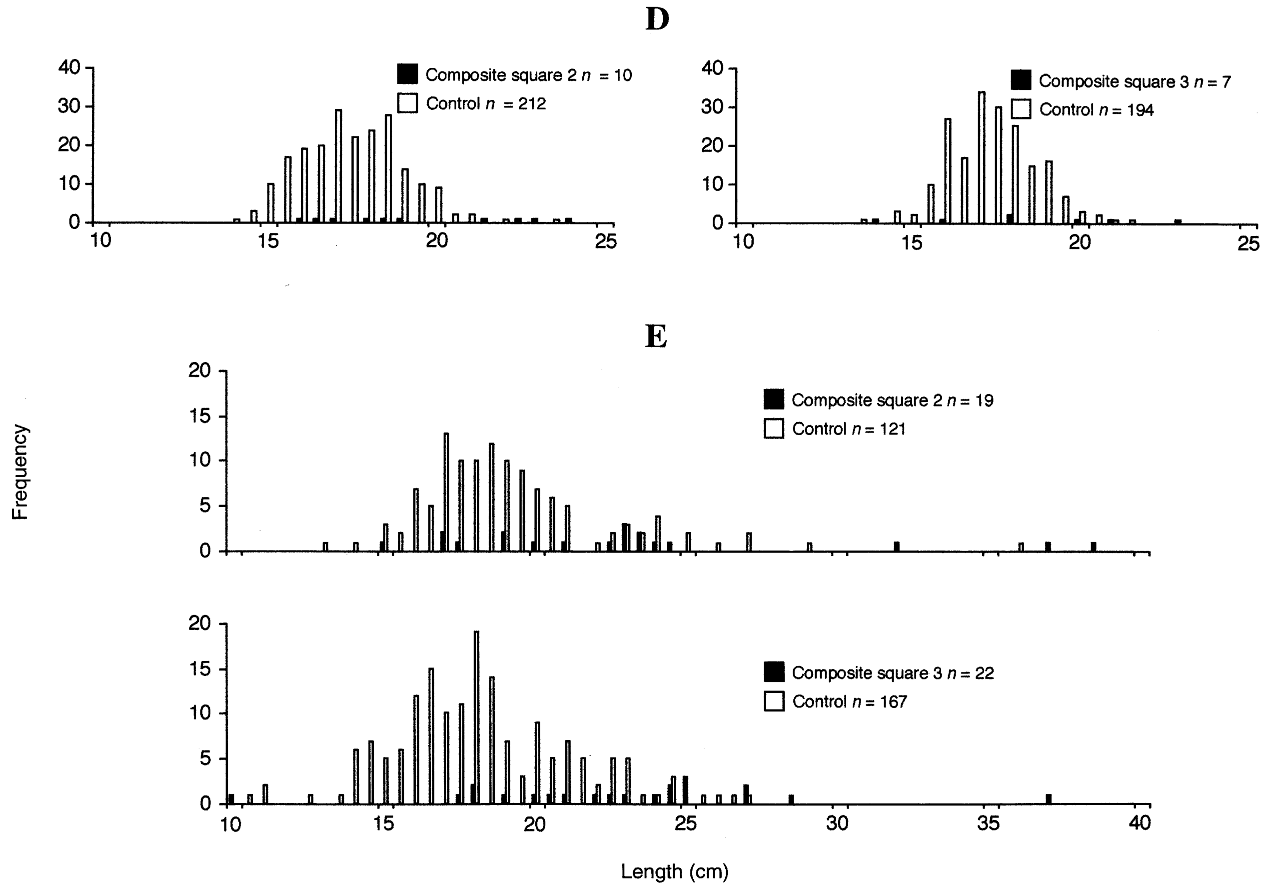

Figure 5 (continued)

used in the posterior section of the codend and the effects that this had on distribution of catch and water flow. Because the posterior diamond-mesh section in this codend was 10 meshes in length, 100 meshes in circumference, and attached to a square-mesh section 62 bars in circumference (hanging ratio of 0.36), as the catch increased it would have spread laterally, increasing its surface area that was incidental to the flow and, therefore, increasing the displacement of water forwards (see Broadhurst and Kennelly, 1996, 1999). The composite-square-3 codend, however, was designed to increase size-selectivity of prawns and was tapered to a circumference of 58 bars attached to a posterior diamond-mesh section that was 2 meshes in length and only 58 meshes in circumference (hanging ratio of 0.57). Combined with lastridge ropes, this configuration would have forced a much smaller codend diameter than in the composite-square-2 codend, restricting any lateral distribution of catch. Any consequent reduction in surface area that was incidental to the flow and displacement of water forwards in this codend (which would limit any assistance to swimming fish) may account for the nonsignificant reduction of Degen's leather jackets and the poorer exclusion of small individuals comprising discarded noncommercial bycatch (Fig. 4D). It should be noted, however, that these results were based on only 11 tows and that further experiments may be required to provide additional evidence to either support or refute the hypothesis discussed above.

Although the mesh configuration and water flow in the composite-square-2 codend may have contributed to the escape of slightly more fish, in terms of optimizing sizes of prawns retained, the composite-square-3 codend appeared to be a better design. Although the 95% confidence limits about the selectivity parameters indicated no significant differences between the two designs (Fig. 6; Table 3), there was some evidence to suggest that the composite-square-3 codend did appear to select slightly more commercial-size prawns. For example, compared with the control, this codend caught significantly fewer prawns by number (difference between means of

Table 2

Length-frequency distributions (pooled across all tows) for prawns captured in the composite square-mesh and control codends, the observed selectivity (ratio of catches), and the fitted logit values. Carapace length in mm; CS2 = composite-square-2 codend; CS3 = composite-square-3 codend.

Carapace length	CS2 codend	Control codend	Observed selectivity	Logit value	CS3 codend	Control codend	Observed selectivity	Logit value
15	0	0	0.00	0.019	0	0	0.00	0.002
16	0	2	0.00	0.025	0	0	0.00	0.003
17	0	0	0.00	0.032	0	0	0.00	0.005
18	0	0	0.00	0.041	0	2	0.00	0.007
19	0	3	0.00	0.052	0	2	0.00	0.009
20	0	3	0.00	0.066	0	2	0.00	0.013
21	0	5	0.00	0.084	0	4	0.00	0.019
22	1	10	0.10	0.106	0	11	0.00	0.026
23	2	7	0.28	0.133	0	7	0.00	0.036
24	0	4	0.00	0.165	0	10	0.00	0.050
25	1	4	0.25	0.204	2	5	0.40	0.068
26	1	6	0.17	0.249	1	8	0.12	0.093
27	4	10	0.40	0.301	0	0	0.00	0.126
28	6	8	0.75	0.357	1	7	0.14	0.169
29	5	10	0.50	0.418	1	2	0.50	0.222
30	10	13	0.77	0.482	4	16	0.25	0.285
31	18	27	0.67	0.546	8	25	0.32	0.359
32	34	42	0.81	0.609	24	27	0.89	0.440
33	43	56	0.77	0.668	48	48	0.10	0.525
34	60	77	0.78	0.723	61	74	0.82	0.608
35	87	96	0.91	0.771	76	112	0.68	0.685
36	116	125	0.93	0.813	105	147	0.71	0.753
37	109	98	1.11	0.849	118	111	1.06	0.811
38	81	77	1.05	0.879	92	62	1.48	0.857
39	60	57	1.05	0.904	63	51	1.23	0.894
40	58	49	1.18	0.924	66	44	1.50	0.922
41	48	48	1.00	0.940	62	49	1.26	0.943
42	53	57	0.93	0.953	63	56	1.12	0.959
43	56	55	1.02	0.964	76	50	1.52	0.970
44	44	39	1.13	0.972	57	46	1.24	0.979
45	31	33	0.94	0.978	32	41	0.78	0.985
46	26	23	1.13	0.983	33	30	1.10	0.989
47	33	18	1.83	0.987	34	18	1.89	0.992
48	33	21	1.57	0.989	29	20	1.45	0.994
49	15	25	0.60	0.992	14	16	0.87	0.996
50	17	10	1.70	0.994	17	9	1.89	0.997
51	13	7	1.86	0.995	12	10	1.20	0.998
52	8	3	2.67	0.996	7	7	1.00	0.999
53	9	2	4.50	0.997	1	5	0.20	0.999
54	9	2	4.50	0.998	2	1	2.00	0.999
55	2	1	2.00	0.998	5	4	1.25	0.999
56	2	2	1.00	0.999	5	3	1.66	0.999
57	4	7	0.57	0.999	2	3	0.67	0.999
58	1	1	1.00	0.999	1	0	0.00	0.999
59	2	0	0.00	0.999	0	1	0.00	0.999
60	0	0	0.00	0.999	1	0	0.00	0.999
61	0	0	0.00	0.999	1	1	1.00	0.999

Table 3

Computed selectivity parameters for prawns (carapace length in mm) from the two composite square-mesh codends and deviance values for logistic curve goodness-of-fit. Standard errors are given in parentheses. *a*, *b* = logistic parameters (Pope et al., 1975). *P* = split proportion from estimated split model (Millar and Walsh, 1992).

	Composite-square-2 codend		Composite-square-3 codend	
a	–7.803		–11.079	
b	0.257		0.338	
P	0.544		0.562	
		95% confidence limits		95% confidence limits
25% retention (L_{25})	26.02 (1.19)	20.14–30.94	29.46 (0.76)	25.42–33.07
50% retention (L_{50})	30.28 (1.19)	28.13–33.38	32.71 (0.82)	31.29–34.59
75% retention (L_{75})	34.56 (1.76)	29.73–42.20	35.95 (1.13)	32.38–40.91
Selection range (SR)	8.53 (0.6)	4.89–12.16	6.49 (0.5)	4.21–8.76
Deviance	32.48		46.54	
df	39		40	
P-value	0.760		0.221	

12.1%) than did the composite-square-2 codend (difference between means of 8.1%), and there was no significant reduction in weights (Fig. 4; Table 1).

These slight differences in size-selectivity of prawns may be explained in terms of the behavior of prawns in the codend and the different configurations of mesh discussed above. Previous studies have shown that the response of prawns to stimuli from the trawl is minimal and after initial contact with the leading edge of the footrope, the prawns are quickly forced into the rear of the codend (Lochhead, 1961; Watson, 1976). Their escape at this point is primarily determined by their probability of randomly encountering openings between meshes that are large enough to pass through. In the composite-square-2 codend, the hanging ratio between the posterior diamond and square-mesh sections would have restricted the fractional diamond-mesh openings, limiting the opportunity for escape. Further, as the catch increased and spread laterally, this would have widened the diameter of the posterior section, providing prawns with less opportunity of encountering any open meshes in the sides of the codend. In contrast, we designed the composite-square-3 codend, so that it would assume a smaller diameter and circumference during fishing, but with a greater area of square mesh, thereby providing more opportunity for prawns to randomly encounter the sides of the codend and the open square meshes.

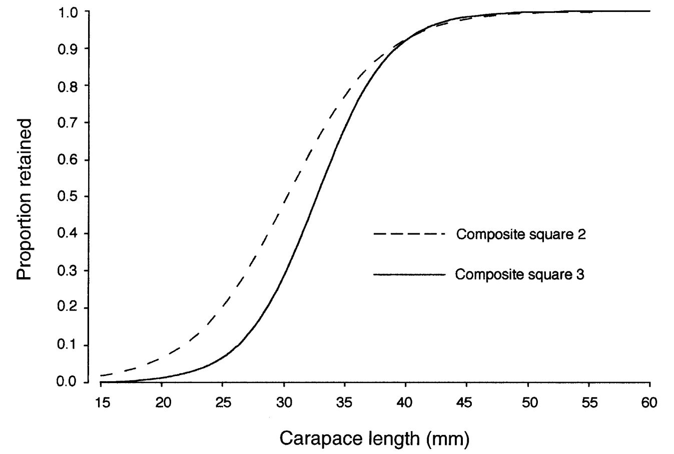

Figure 6

Size-selectivity curves for king prawns (*Penaeus latisulcatus*) from the composite square-mesh codends.

The results obtained in this study showed that composite square-mesh codends in penaeid prawn trawls can improve size-selectivity of the targeted prawns while reducing large quantities of unwanted fish. It is also apparent, that such modifications may improve the overall efficiency of the trawl in terms of increasing catches of prawns. For example, although the composite-square-2 and square-3 codends significantly reduced the numbers of prawns caught by 8.7% and 12.1%, compared with the control, the differences in weights of prawns were much smaller, to the point where they were nonsignificant (e.g. 1.8% and 3.7%, respectively). To achieve such a result, the two trawls containing composite square-mesh codends caught more prawns but retained mainly larger-size individuals.

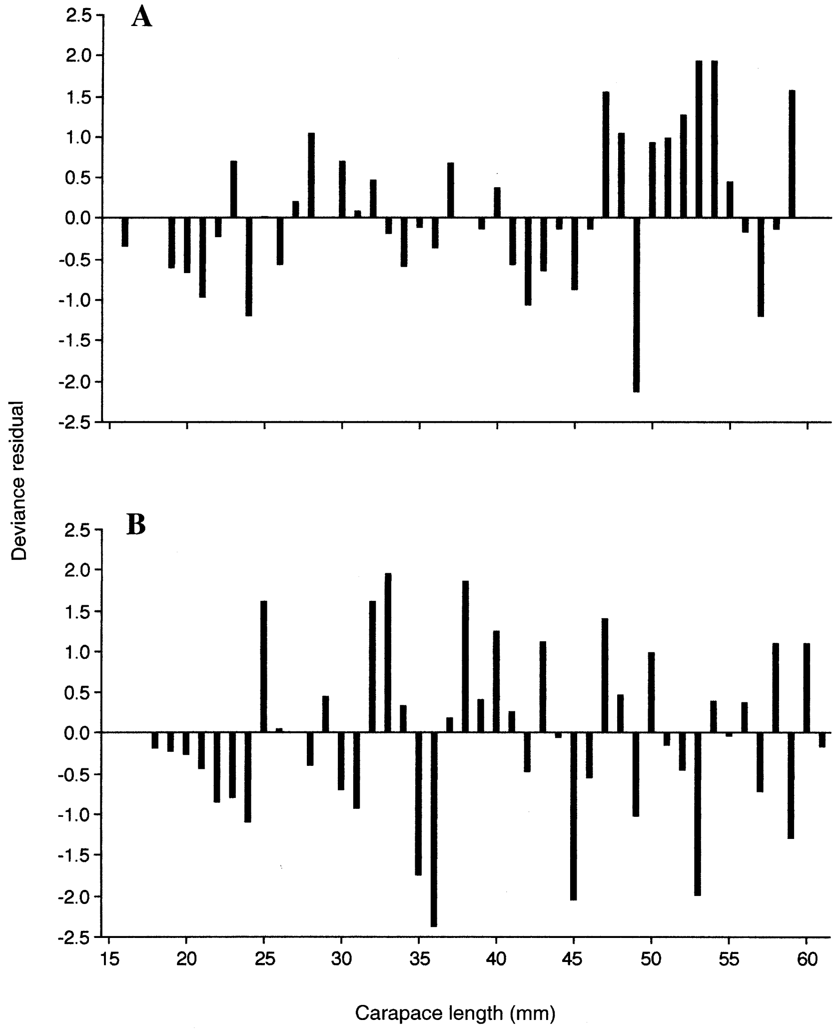

Figure 7

Plots of the deviance residuals from selection curves for the (**A**) composite-square-2 codend and (**B**) composite-square-3 codend.

One hypothesis to explain this result is that the large, open, square meshes in the composite square-mesh codends, combined with the overall size of the codends (approx. 4 m in length) allowed a faster release of water from the body of the trawl than did the control. Such an increase in flow may have resulted in prawns quickly passing into the codend after initial contact with the footrope, with less chance of randomly escaping over the headrope or out through the mouth of the trawl. In support of this, Walsh et al., (1992) provided evidence of similar flow-related effects on the catches of fish (American plaice, *Hippoglossoides platessoides*) from trawls fitted with square-mesh codends. In the present study, however, any potential effects of increased flow did not appear to influence fish such as small-toothed flounder (the only species that could not pass through the square mesh), because there were no significant differences in the catches between the composite square-mesh and control codends (Table 1). An alternative hypothesis proposed by Broadhurst and Kennelly (1997) to describe a similar increase in catches of prawns from NSW oceanic prawn trawls containing codends with composite square-mesh panels is that by reducing the weight of bycatch and therefore the drag in the codend, trawls with the composite square-mesh achieved slightly more swept area than did controls, thereby covering more of the sea bed and capturing more prawns.

Regardless of the underlying mechanisms, the increase in catches of target-size prawns, combined with the substantial reductions in the bycatch of fish, led to unanimous industry acceptance and adoption of the composite-square-3 codend within two weeks of the conclusion of the field work described in this paper. Fishermen have since reported that the codend has minimal distortion (due to the lastridge ropes), allows increased tow duration, and provides an improved quality of prawns. These results illustrate the benefits that can be derived through liaison with industry and by incorporating their ideas into modifications to improve the selectivity of prawn trawls. Such voluntary adoption should ensure the continued development and refinement of designs, as part of normal commercial operations.

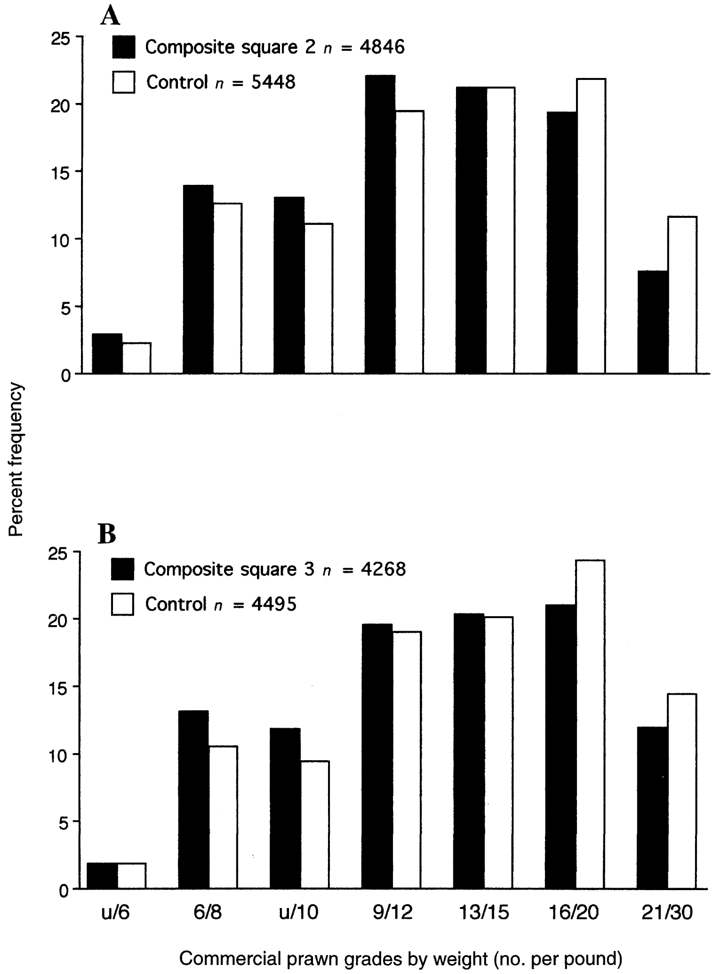

Figure 8

Commercial size categories of king prawns (*Penaeus latisulcatus*) caught with the (**A**) composite-square-2 and control codends and (**B**) composite-square-3 and control codends (u=under).

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Appendix

The plots of deviance residuals (Fig. 7) for both selection curves provided in Figure 6 showed that most of the size classes of prawns above 45-mm carapace length had high deviances. By removing these data from analysis and also the frequencies for the 35- and 36-mm size classes from the composite-square-3 codend, the *P*-values for model goodness-of-fit increased from 0.760 to 0.999 for the composite-square-2 codend (df=25) and from 0.221 to 0.853 for the composite-square-3 codend (df=21) (Table 4). Although this alternative analysis does provide selectivity parameters that are slightly different from those calculated in Table 3, the overall interpretation of the data remains the same.

Table 4

Computed selectivity parameters for prawns (carapace length in mm) from the two composite square-mesh codends and deviance values for logistic curve goodness-of-fit, excluding all entries above 45-mm carapace length for both codends and the 35- and 36-mm size classes from the composite-square-3 codend. Standard errors are given in parentheses. *a*, *b* = logistic parameters (Pope et al., 1975). *P* = split proportion from estimated split model (Millar and Walsh, 1992).

	Composite-square-2 codend		Composite-square-3 codend	
a	–9.556		–13.58	
b	0.330		0.424	
P	0.513		0.573	
		95% confidence limits		95% confidence limits
25% retention (L_{25})	25.59 (0.60)	21.80–29.17	29.46 (0.59)	26.33–32.38
50% retention (L_{50})	28.92 (0.63)	27.73–30.42	32.05 (0.66)	30.90–33.67
75% retention (L_{75})	32.24 (0.92)	28.68–36.64	34.64 (0.96)	31.77–38.67
Selection range (SR)	6.65 (0.92)	4.84–8.45	5.18 (0.81)	3.42–6.95
Deviance	7.91		14.75	
df	25		21	
P–value	0.999		0.853	